DXOMARK

FOCUSED ON EXCELLENCE

The Machine Intelligence of Image HDR Formats

Summary

I. Physical and Physiologic Reminder

II. HDR ecosystem

III. Video HDR - format fundamentals

IV. Video HDR - delivering the potential

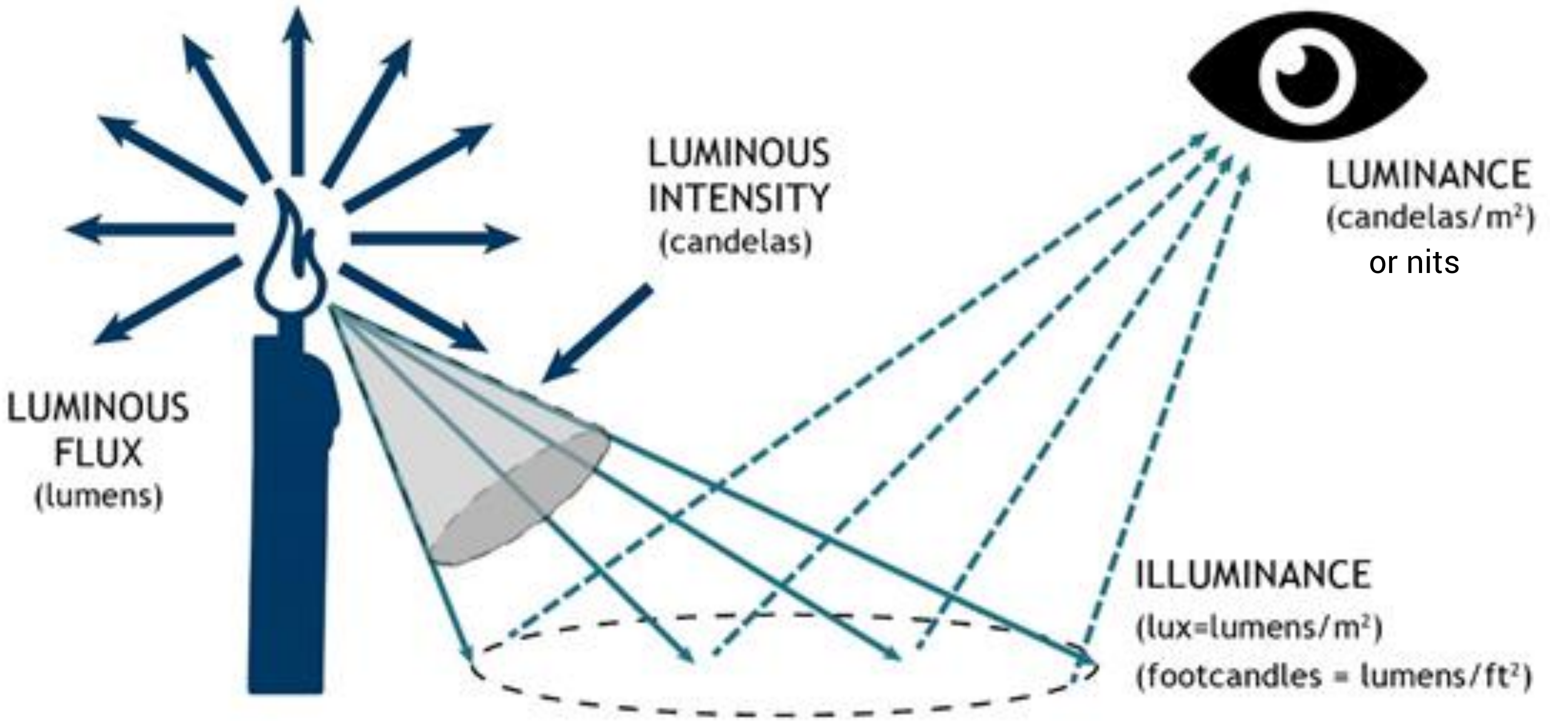
V. Photo HDR – fresh news

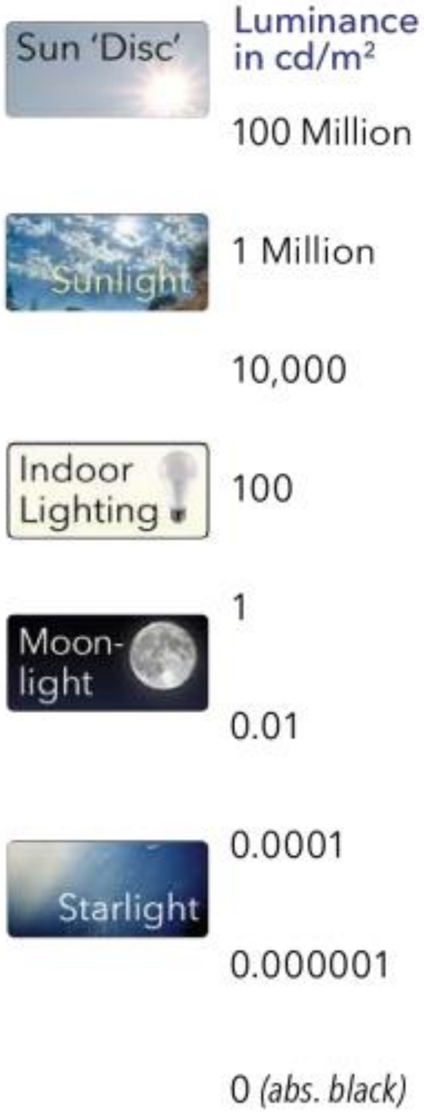
VI. Challenges for Image Quality

Physical and Physiological reminders

What do you look at and how do we perceive it?

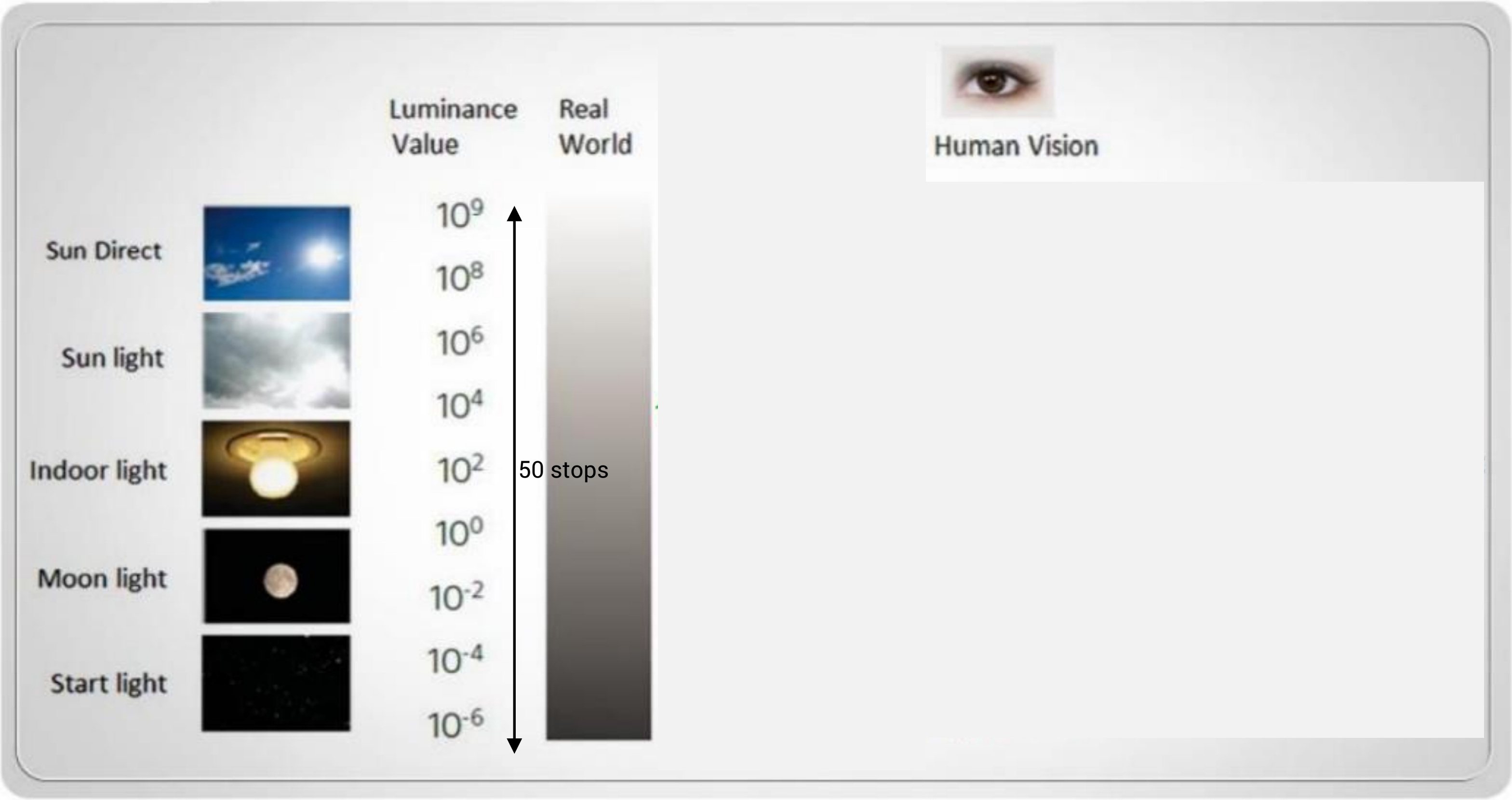
Physical reminder



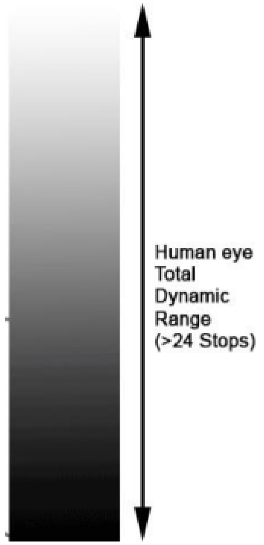


https://luminusdevices.zendesk.com/hc/en-us/articles/4403668356109-What-s-the-Difference-Luminance-Luminous-Flux-Illuminance-Luminous-Intensity-Lux-Lumens-

Physical reminder



Cd/m²

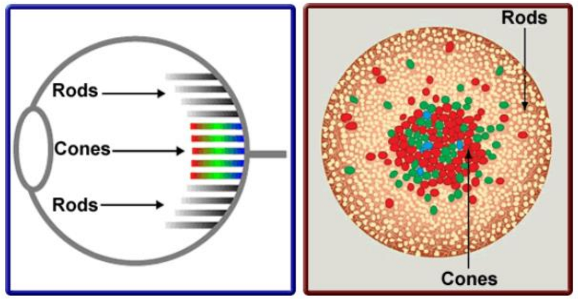


Physiologic Reminder

- Luminance ranges of the Human Visual System:
  - **Photopic**: 10 to 10^8 cd/m^2 (cones only (LMS) in bright outdoors)
  - **Mesopic**: 10^{-3} to 10 cd/m^2 (cones + rods (LMS+Y) in indoor or outdoors at night)
  - **Scotopic**: 10^{-3} to 10^{-6} cd/m^2 (rods only (Y) in near-darkness, moonlight)
- Recovery times of the HVS to luminance changes: (cit)
  - Cones take up to **2 min** to recover in the dark after bright light adaptation
  - Rods take up to **20-40 min** to recover in the dark after bright light adaptation

Biological mechanisms for adaptation

- **Changes in pupil diameter** (closed-loop aperture control)
- **Bleaching adaptation** (closed-loop exposure control)
- **Rods/cones physically connected** (local exposure fusion)

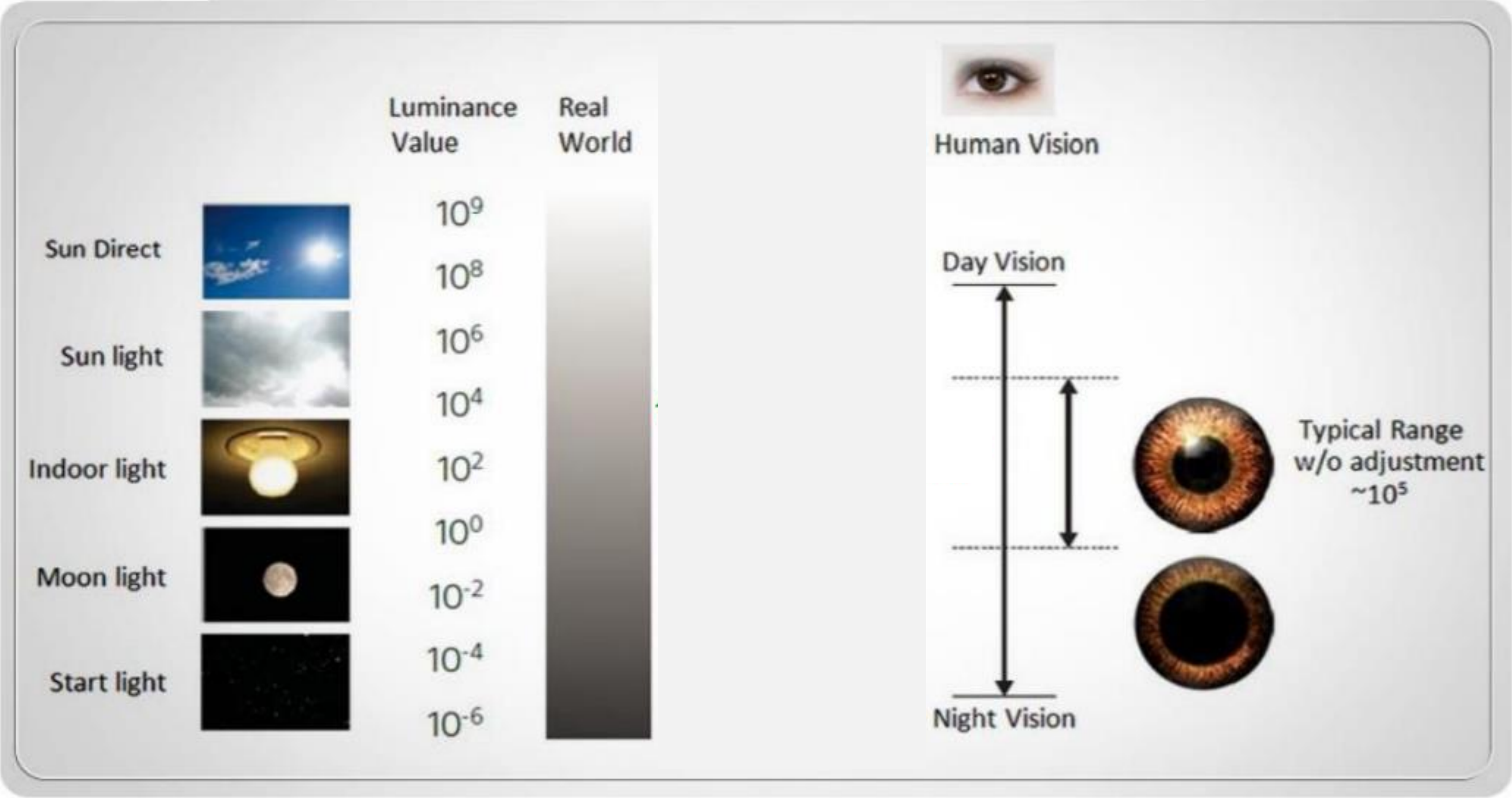


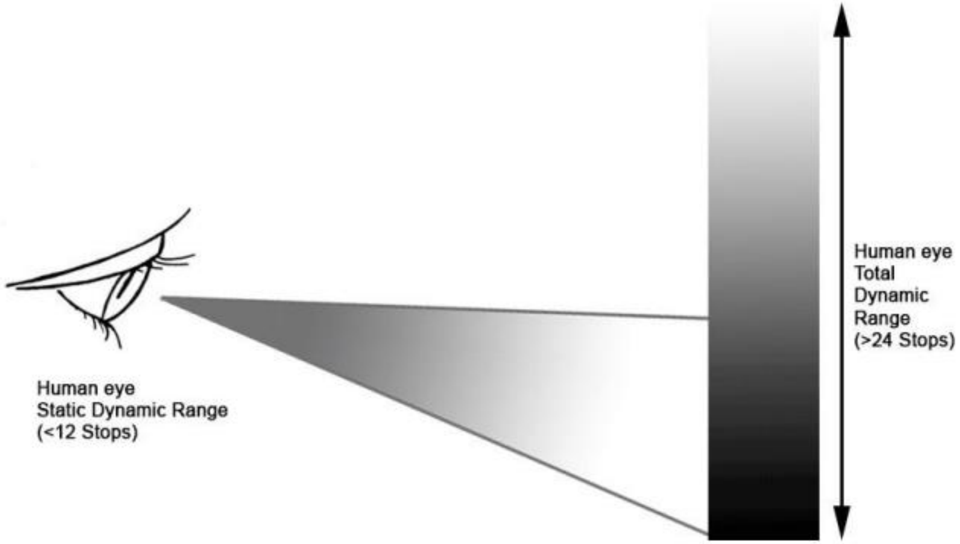
Luminance (cd/m^2)	0.001	0.01	0.1	1	10	100	1000	10000
Pupil Diameter (mm)	7.3	7.1	6.5	5.6	4.2	3.1	2.3	2.0
Pupil Area (mm^2)	42.2	39.4	33.6	24.2	14.1	7.4	4.3	3.1
Retinal Illuminance (troland)	0.042	0.39	3.4	24	141	736	4309	31286

Table 1. Luminance, Pupil Size and Retinal Illuminance (troland)
(Pupil sizes predicted from Watson-Yellot model for 30-degree stimulus)

Eye image via https://biologywedscomputer.wordpress.com/2016/06/22/the-pirates-eye-patch/
Table/graph via "*HIGH DYNAMIC RANGE, VISUAL ADAPTATION, AND CONSUMER PERCEPTION: APPLYING VISUAL SCIENCE IN THE SEARCH FOR CONSENSUS ON HDR*", Sean T. McCarthy, Ph.D.

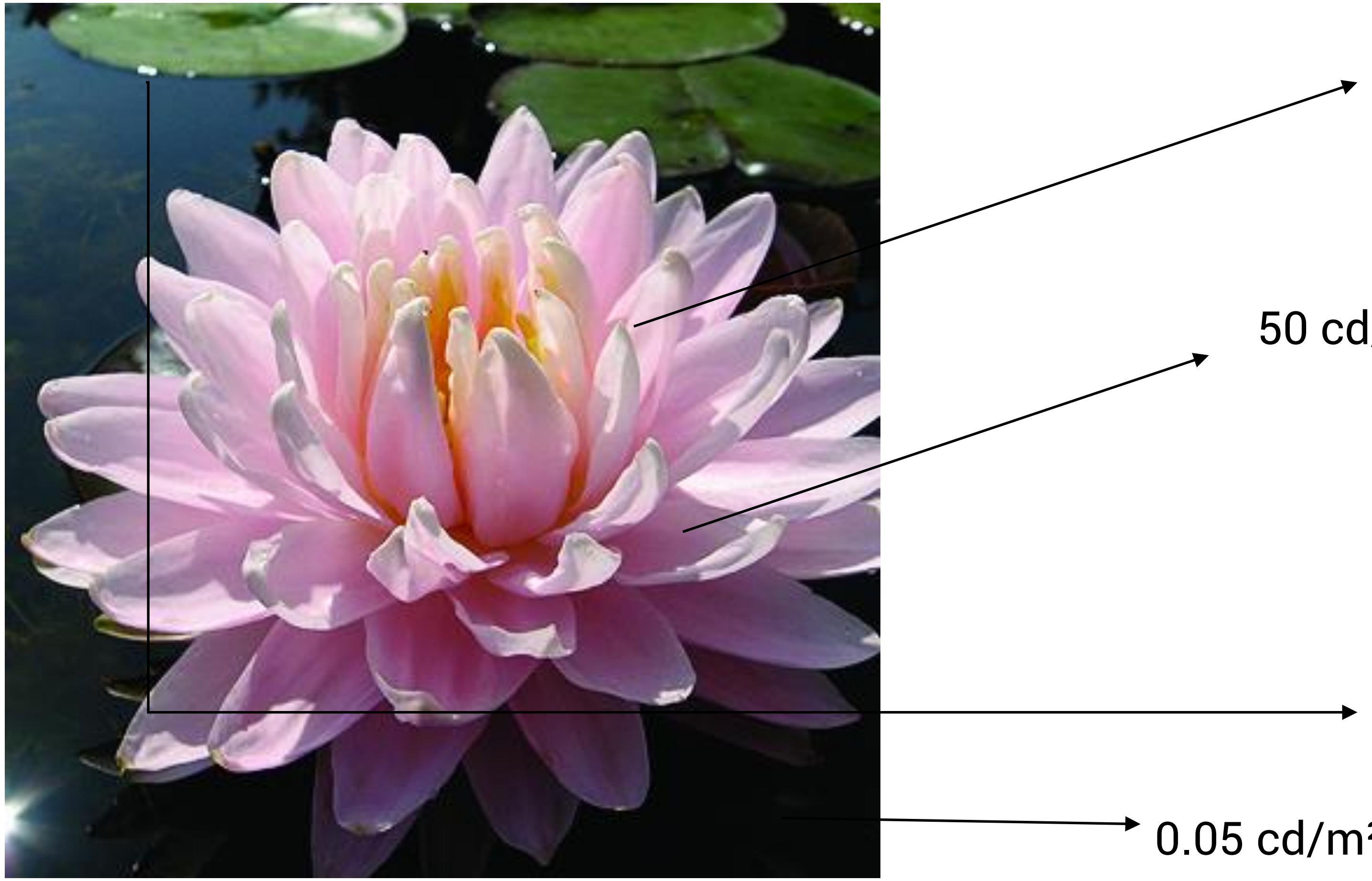
Restitution





Dynamic Range in a scene

Color science is mostly based on scenes where light source is incident on a surface and reflected.



Dynamic Range in a scene

In real life scene is lit by multiple sources, and may contains emissive light sources

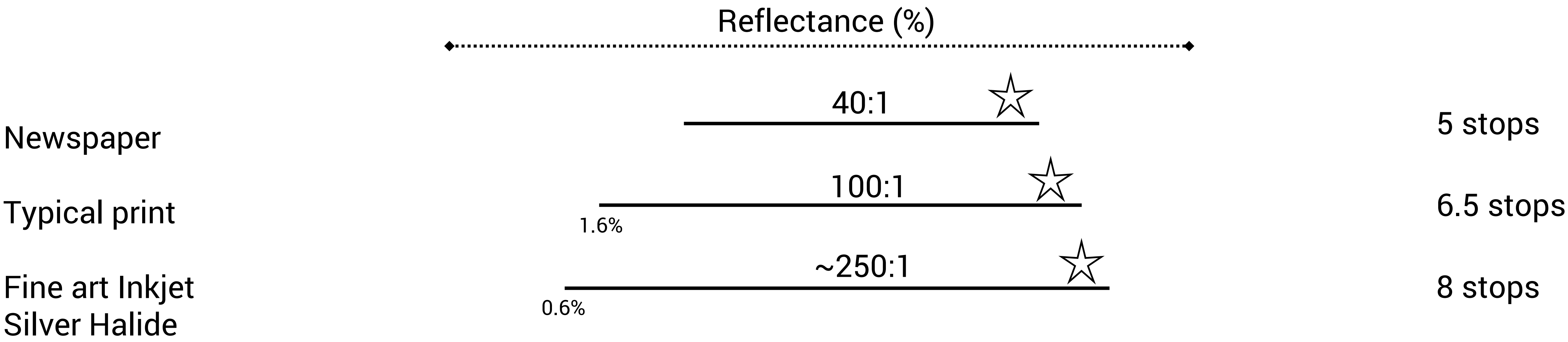
Emissive light source

Reflection
White Diffuse
Point ?

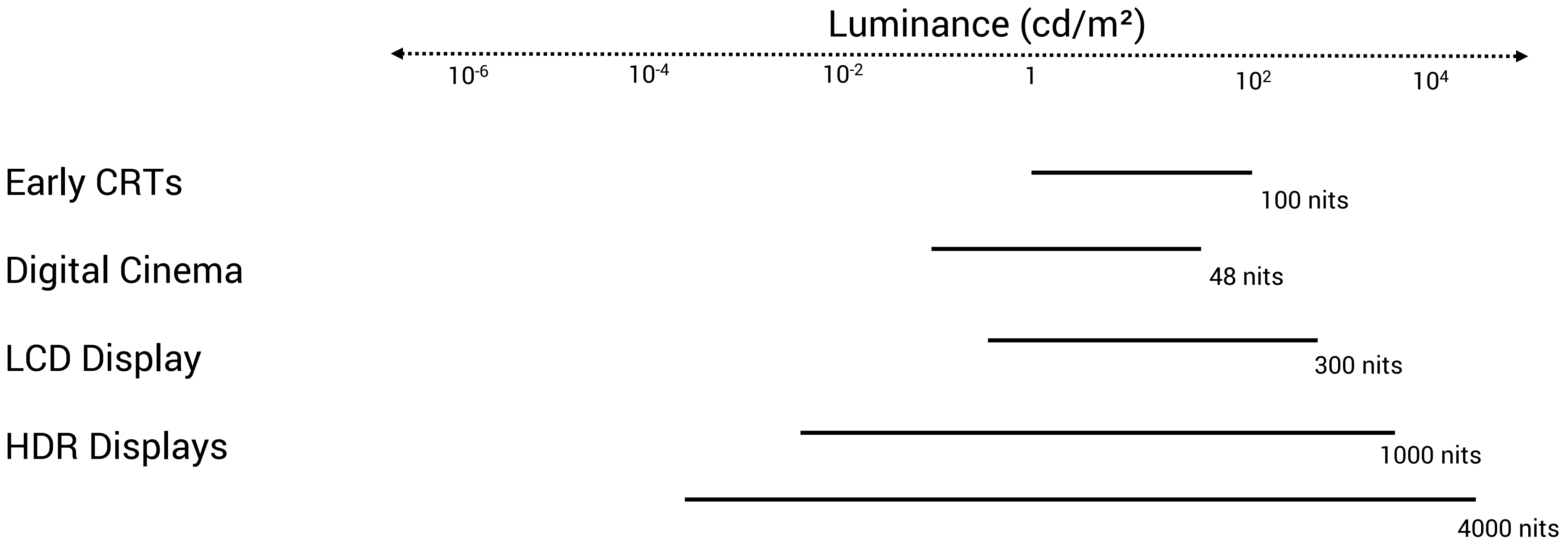
Point Source

Specular
Highlights

Restitution - prints



Restitution - Displays



Restitution and Human Vision System

The HVS is able to accept high compression of the dynamic range.

Artists know how to compress the scene range by many stops for centuries.

John Singer Sargent. The Daughters of Edward Darley Boit. 1882. Museum of Fine Arts, Boston

Actual light dynamic was probably much larger than 1000:1, but is rendered beautifully in 100:1 medium.

HDR Ecosytem

HDR Capture, HDR Display, HDR Format

HDR, The catch-all term

HDR Capture :

- capture as much light as possible from the scene, by hardware sensors, multi-frame and computational photography fusion…A HDR representation of the scene is necessary.

HDR Compression :

- Process to render the HDR representation to a much smaller SDR range display.
- The process is called color and light grading or tone mapping.

HDR Displays :

- Displays with higher luminance range than the standard range. Televisions, smartphones, tablets, and computer displays are rapidly moving to HDR technologies. Such display have a “headroom” to display brighter luminance range compared to standard range.

HDR Format :

- Format defining how to store HDR representations, in order to display them on HDR display.
- Initiated by Cinema (Dolby Cinema), then TV and Broadcast (Dolby Vision, HDR10, HDR10+), and moving to still photography (JPEG XL, HEIF, ISO 22080-5, …)

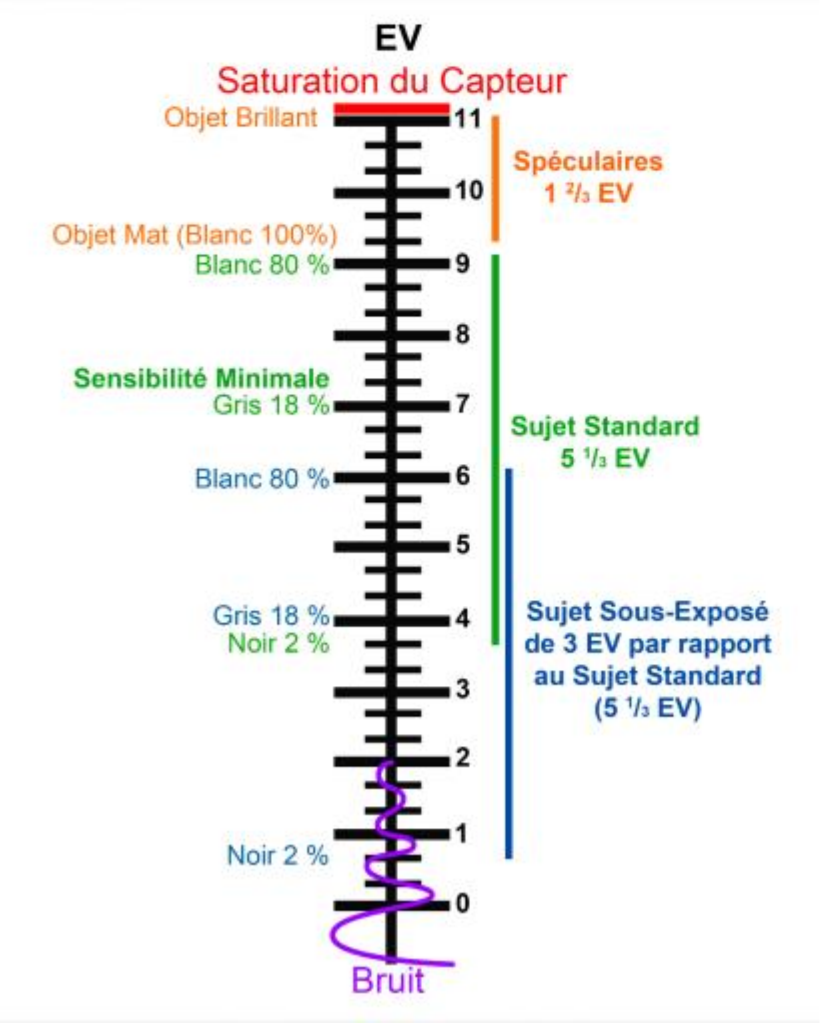
HDR capture

Diffuse object under diffuse light
4 Stops

Diffuse object under diffuse light
with deeper shadows
7 Stops

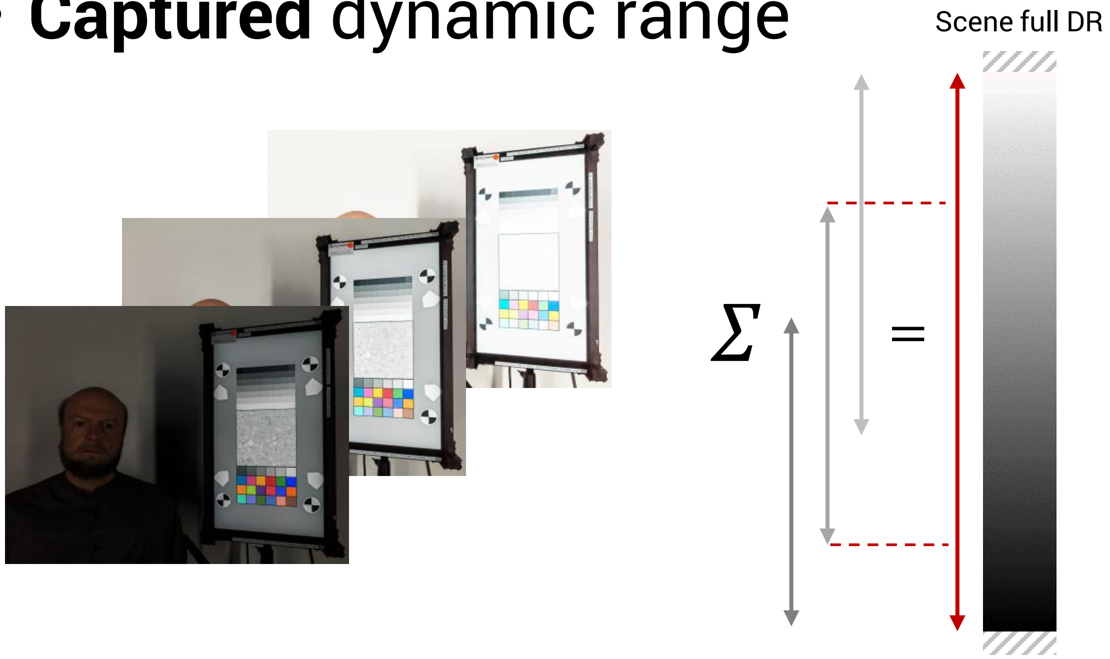
Hard light with deeper shadows
9 Stops

Artificial light with deeper shadows
14 Stops

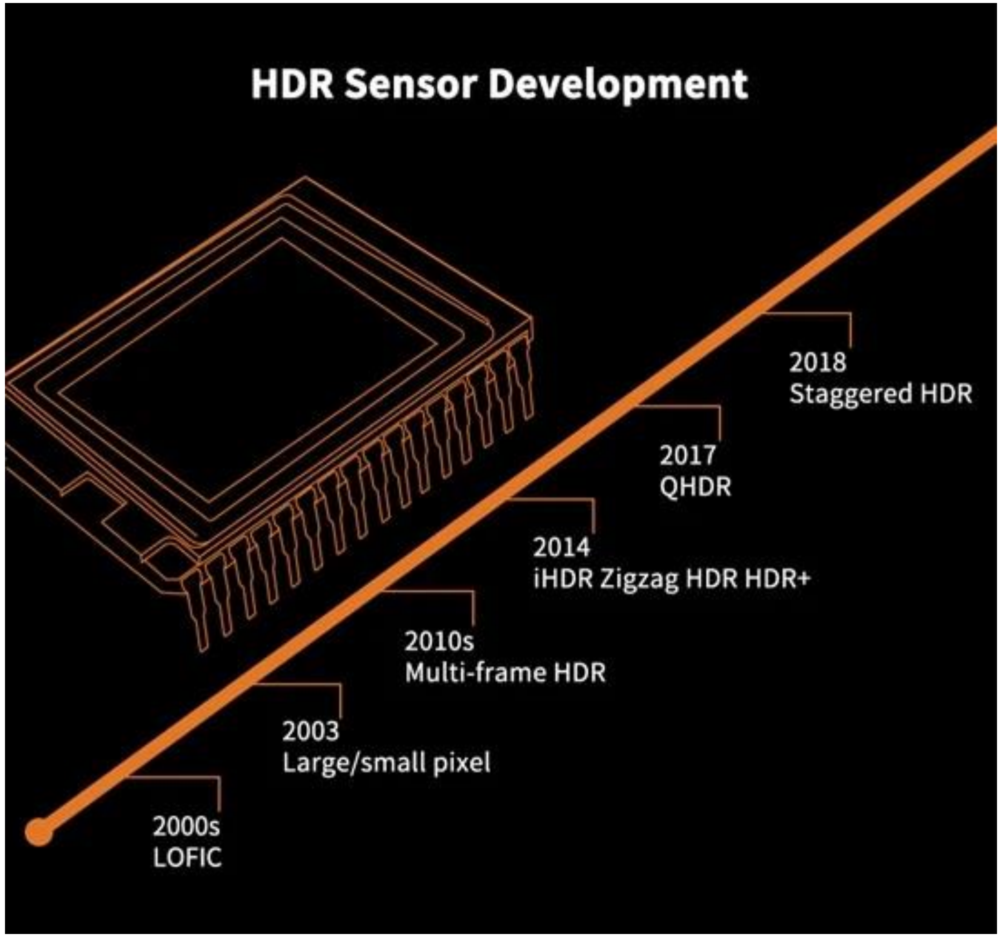


HDR Capture: technological progress

- **Captured** dynamic range



- Bracketing, multi exposition => gain of dynamic range
- For smartphones (7 stops ➔ 15 stops)
- Real-time bracketing is more challenging
- Artifacts created by bracketing



https://www.eetimes.com/hdr-the-secret-behind-great-images/

HDR Tone Mapping

“ HDR Tone mapping is the art and science of getting from a large HDR range down to a much smaller SDR range while maintaining the perception of the original scene range. “

Basically do what Sargent and Rembrandt are doing by computational means.

- Global Tone Mapping
- Local Tone Mapping

Becareful to:
- Visualization Scales
- Halos
- Tonal Inversion

Open window with armchair and manequin.
Sample scene for HDRI, tone mapped using different operators.
In clockwise order: **Reinhard** (Photographic Tone Reproduction), **Fattal** (Gradient Domain HDR Compression), **Mantiuk** (A Perceptual Framework for Contrast Processing of High Dynamic Range Images), **Reinhard** (Dynamic Range Reduction inspired by Photoreceptor Physiology).

HDR Display

HDR developed for the **Cinema**

Reflection > 90% (white)

Then, HDR has been developed for the **Live TV**

Reflection < 3% (AG,AR coating)

And now HDR for **Smartphone !**

Reflection ~ 5% (AR only)

AR: Anti-Reflection coating
AG: Anti-Glare coating

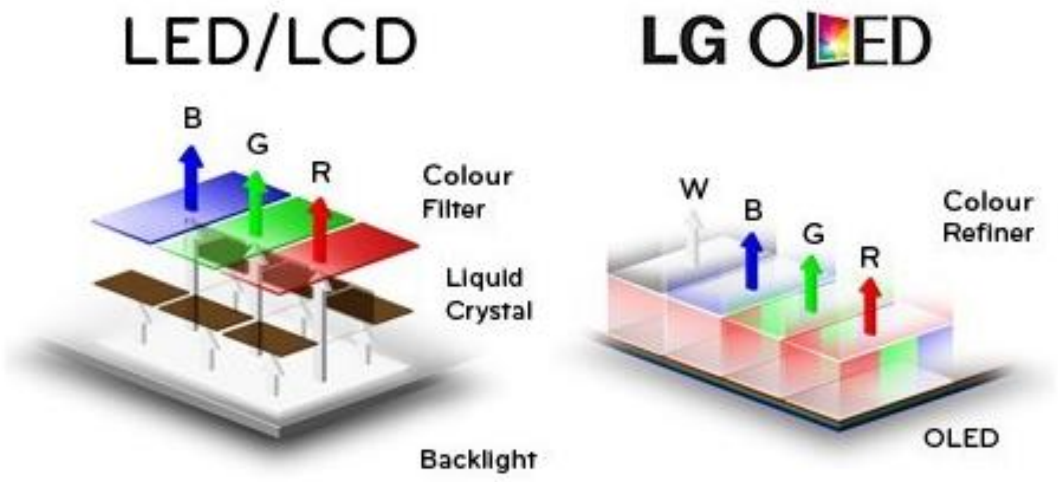
HDR Displays

- **Displayed** dynamic range

- Max : power limitation of LED or backlight
- Min : LCD (lead)
- Feeling of contrast

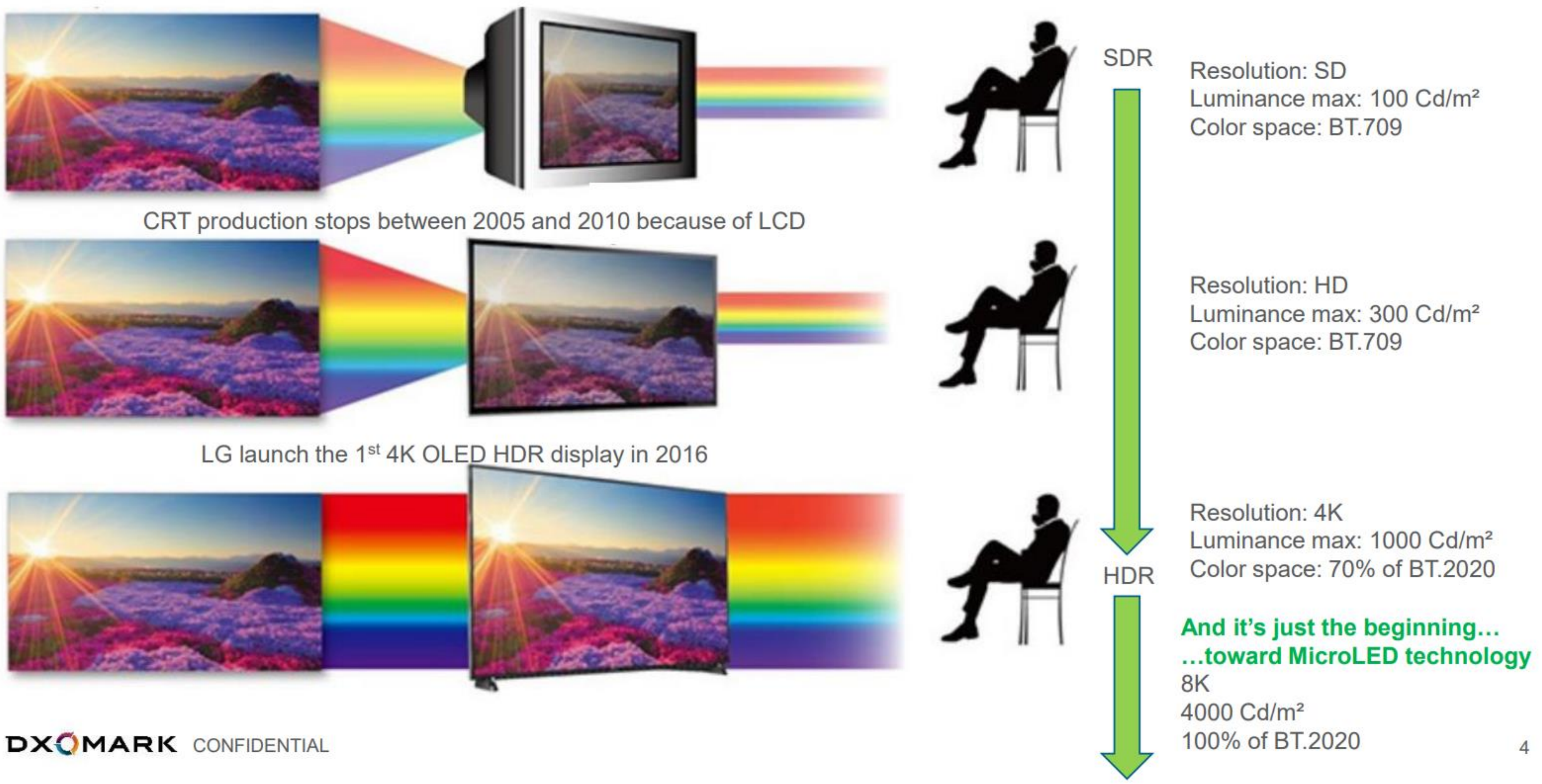
Ex : HDR format, contrast ratio in display specs

- **Displayed** dynamic range

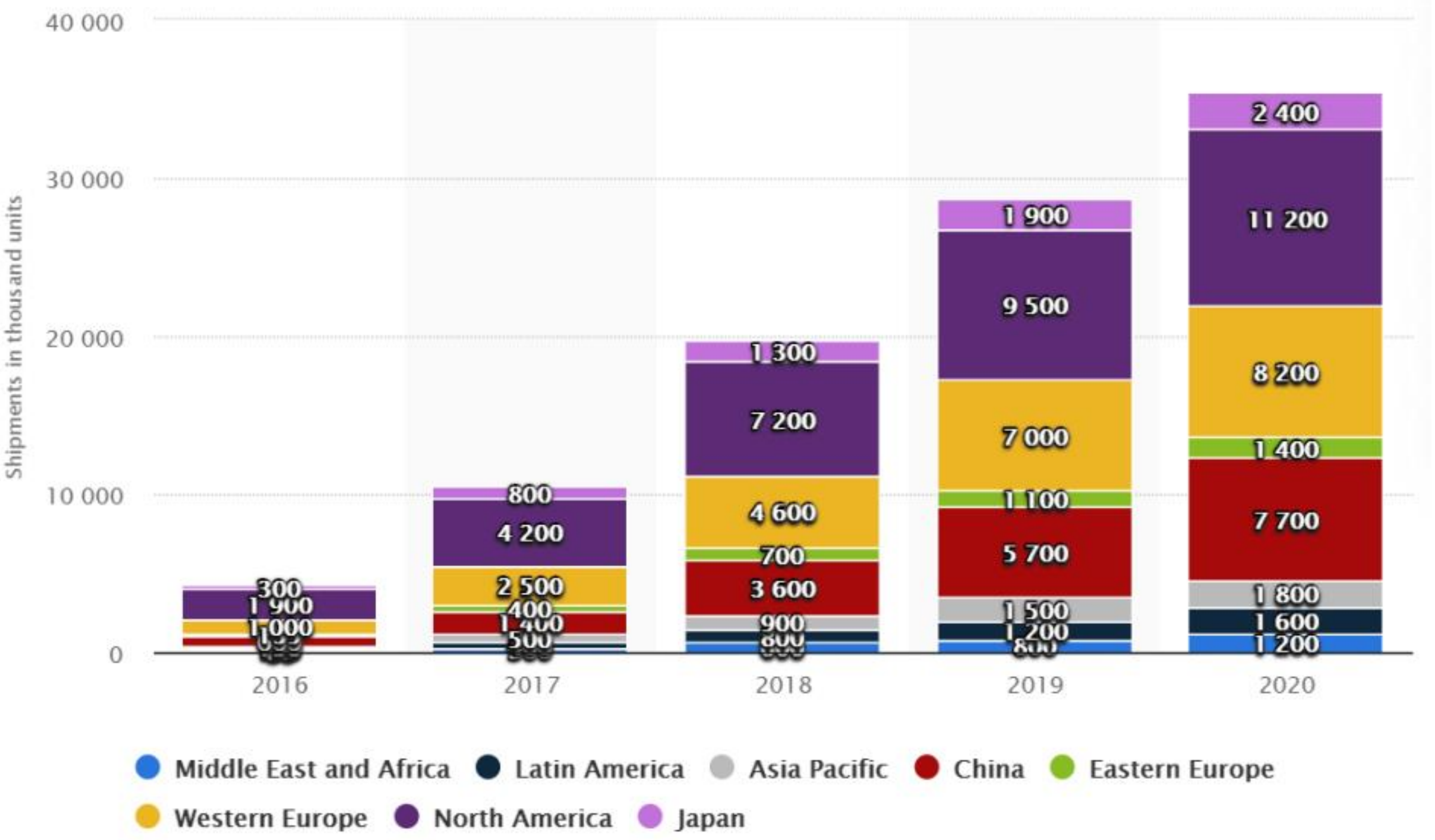


- HDR displays :
  - OLED : 0,0005 – 540 nits
  - Backlit LCD : 0,05 – 1000 nits
- Recent technological progress, most displays are still SDR
- Max 4000 nits (Dolby Pulsar)

HDR Displays



HDR TV extension



HDR Reference Display

Apple XDR
IPS LCD
1000 nits (1600nits HDR)
P3 wide color gamut
5000$

Sony BVM HX 310
Dual LCD
1000 nits
BT.2020
33000$

Dolby Pulsar
?
4000 nits
?

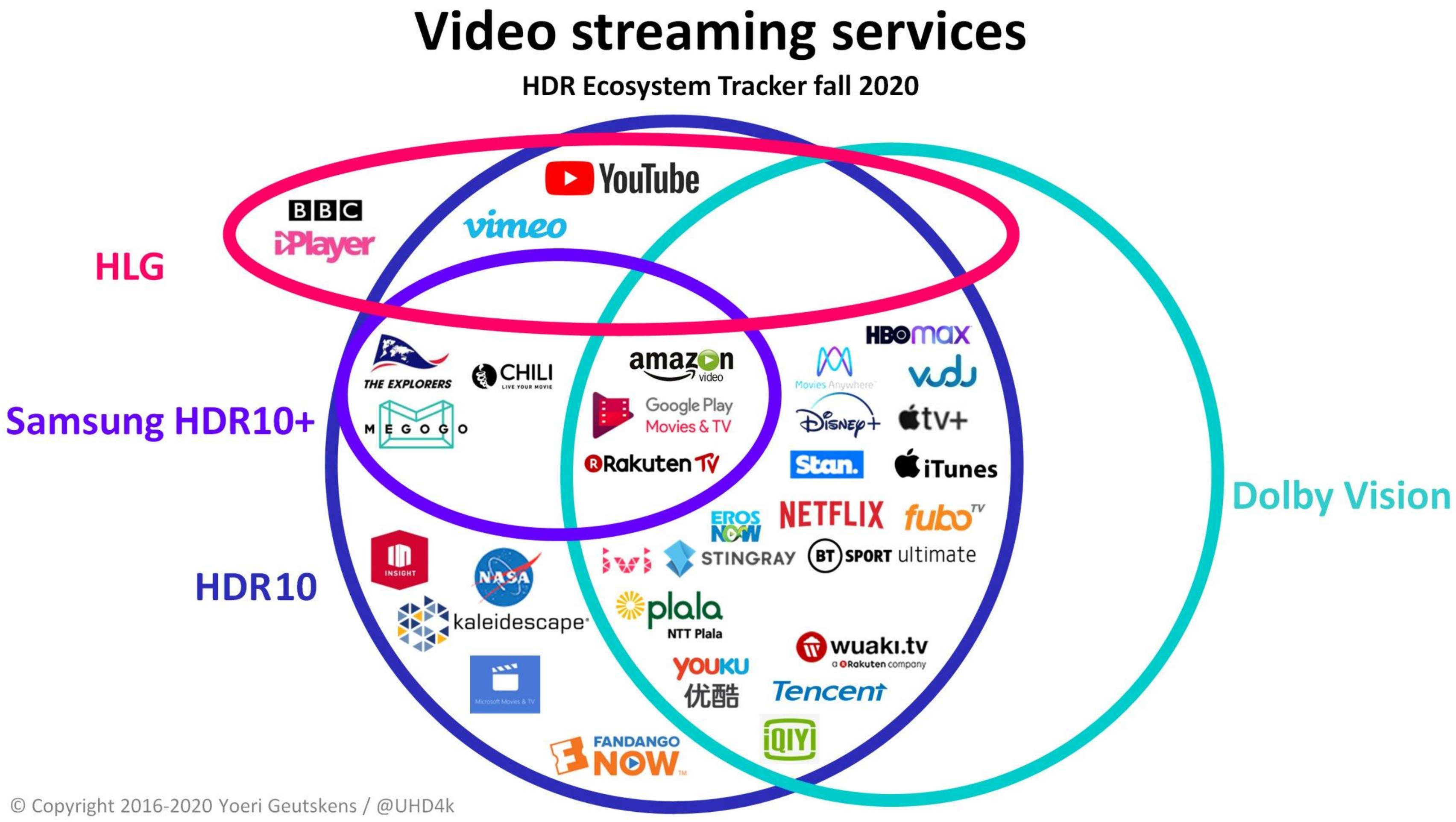
HDR Format

- Conveying high dynamic range contents
- Define metadata for correct interpretation

HDR Technology Video	Company	Country	Date	Fee
Dolby Vision / Dolby Cinema	Dolby Lab	US	2014	Dolby Certification, not free
HDR10	Samsung + Consortium	Korea	2015	Certification, free
HLG	NHK / BBC	Japan / UK	2015	Free
Dolby Vision IQ	Dolby Lab	US	2021	Dolby Certification, not free
HDR10+	Samsung + Consortium	Korea	2017	Certification, free
Vivid HDR	Huawei	China	2020	? Free

HDR Technology Photography	Company	Country	Date	Fee
JPEG-XT JPEG-HDR	Disney/Brightlight → Acquired by Dolby	US	2005 2007	Not free
	Apple	US	2020	Closed
ISO-22028-5 Gain Map	Apple / ISO	US	2023	Free

HDR ecosystem (Fall-2020)



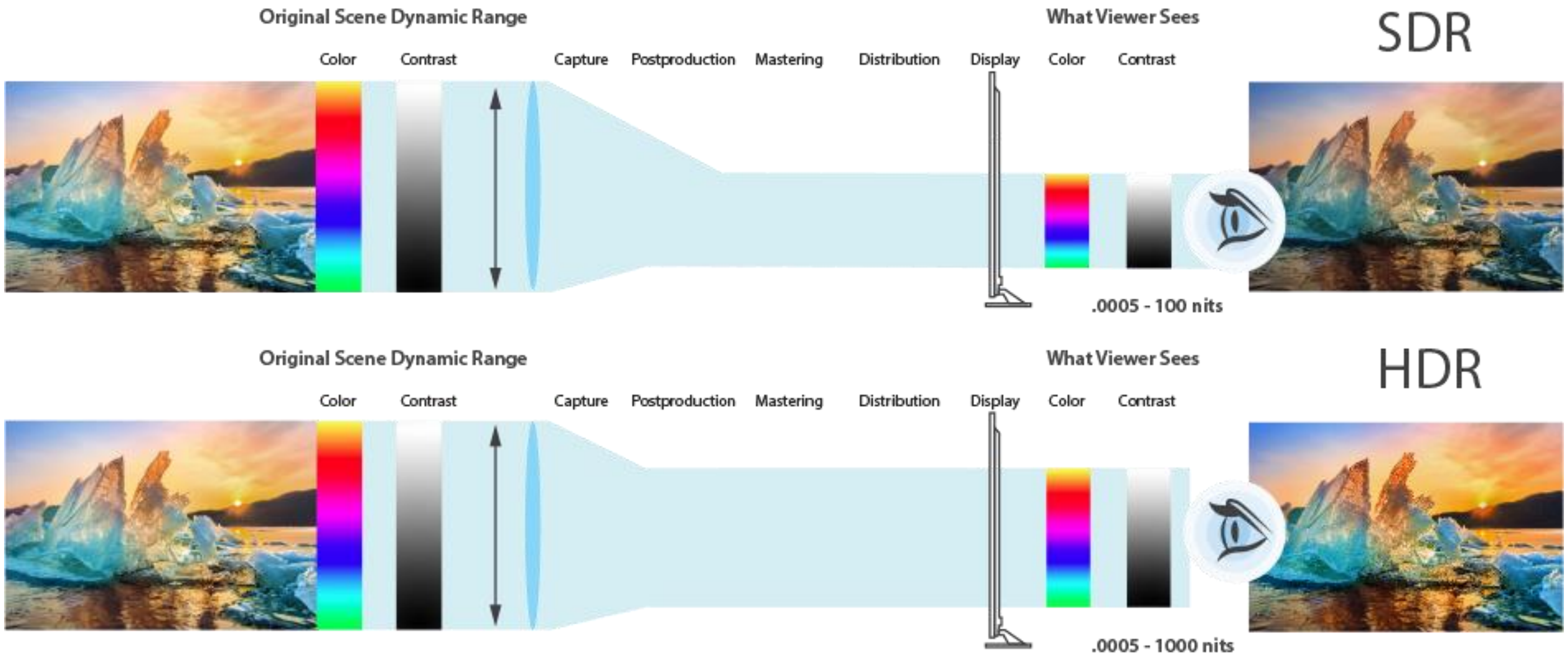
See also for :
- Broadcasters
- Operators
- Smart TV

Video HDR format

Fundamentals: OOTF, Luminance Encoding, Wide Color Gamut

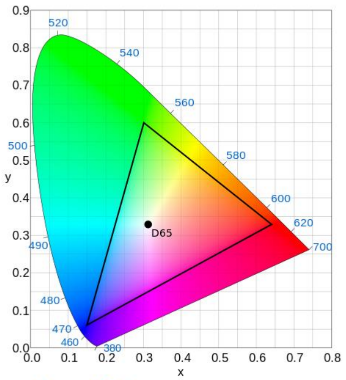
From the original scene to the human eye: the challenge of HDR pipeline

HDR video format were born because the display panels have improved

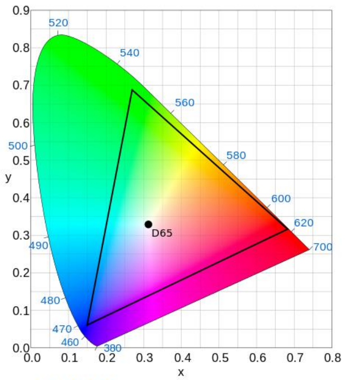


Creating more-defined contrasts and richer colors

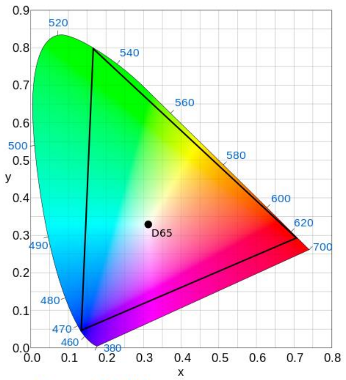
Improves image fidelity



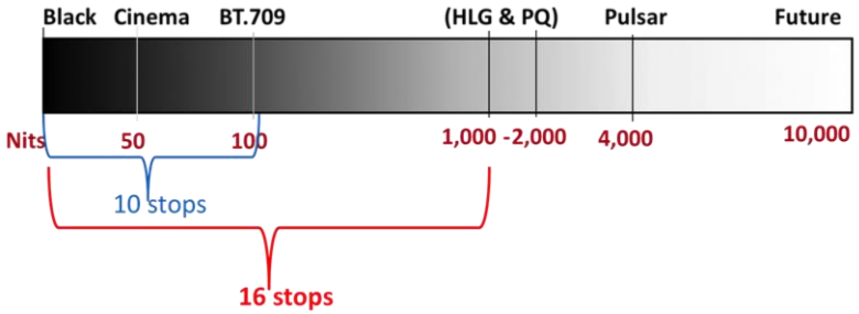
Rec. 709
35.9% of visible spectrum

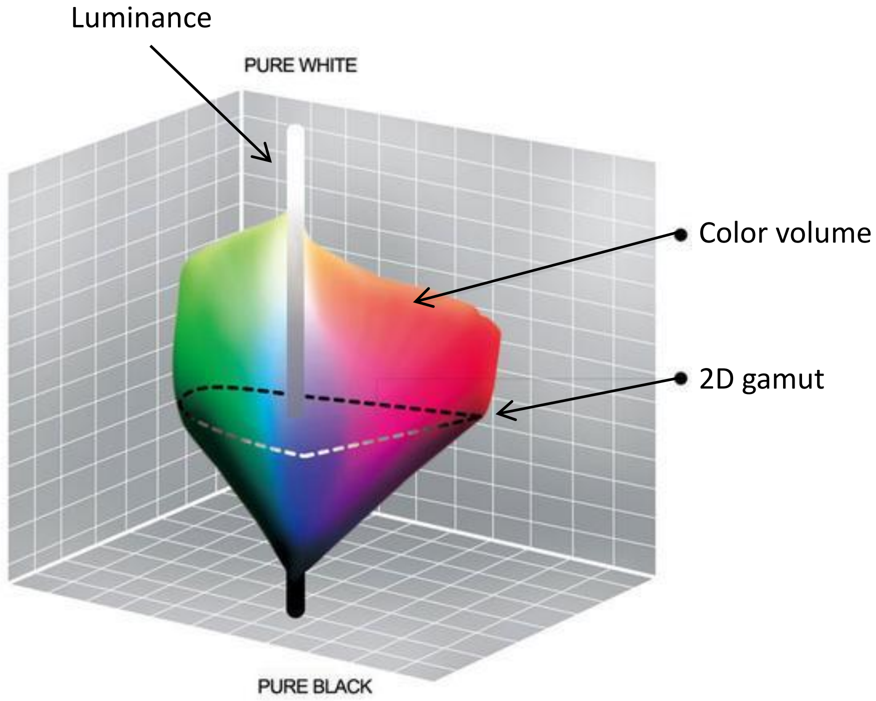


DCI-P3
45.5% of visible spectrum

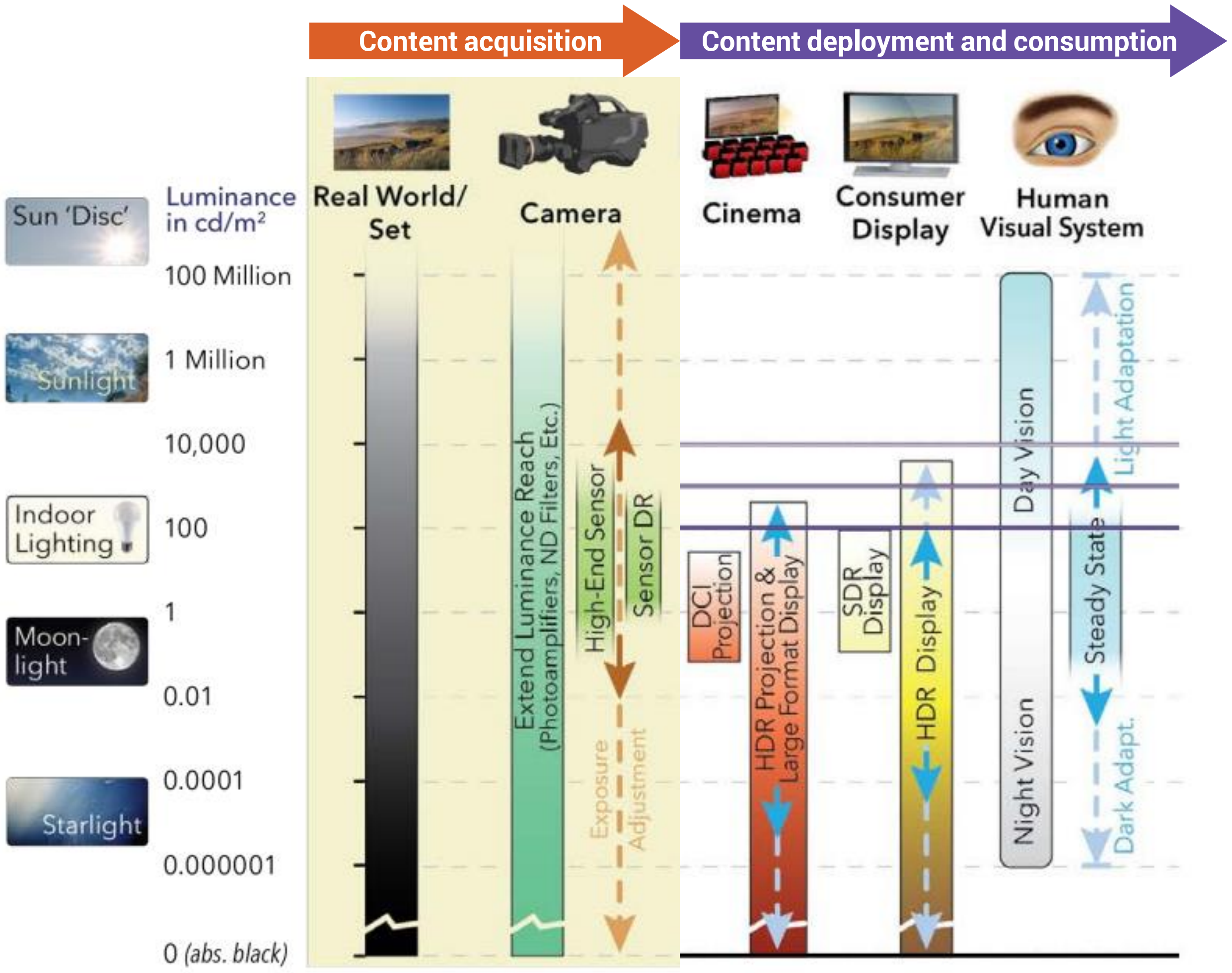


Rec. 2020
75.8% of visible spectrum



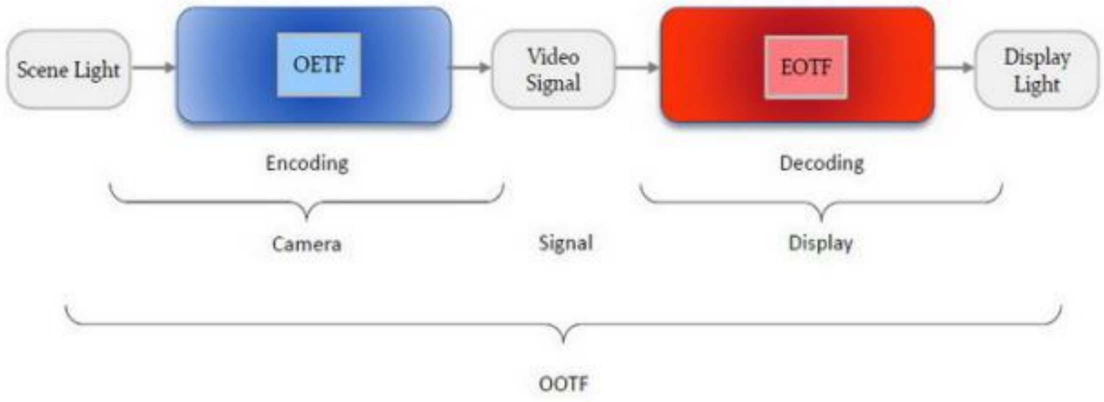


Transfer function needs human decisions - OOTF

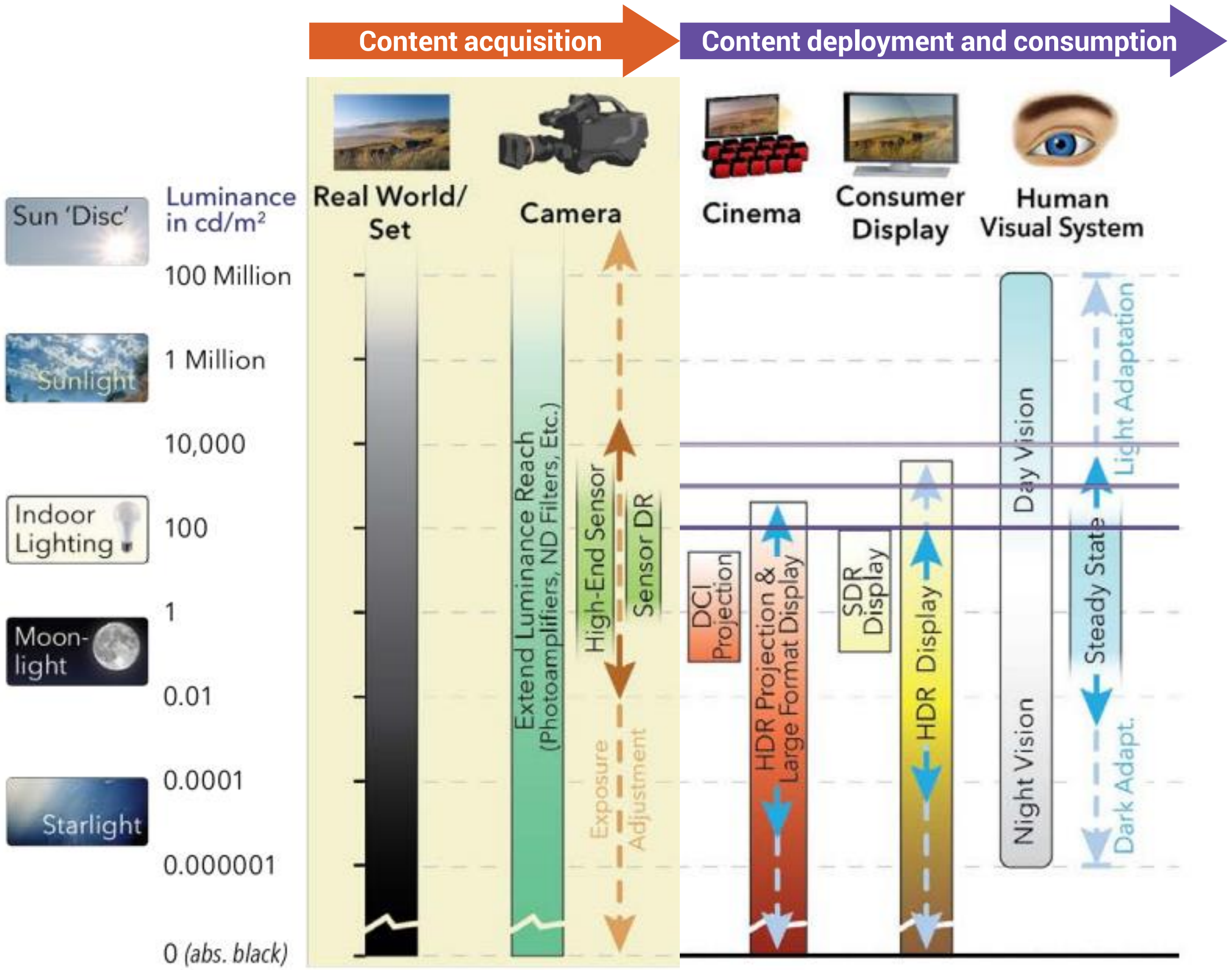


*The Perceptual Quantizer Design Considerations and Applications TIMO KUNKEL, PHD DOLBY LABORATORIES, INC. SAN FRANCISCO, CA © 2022 DOLBY ICC HDR EXPERTS DAY – MARCH 15, 2022

- **Human decisions** are necessary to fit higher dynamic range of the scenes into the standard range



Transfer function needs human decisions

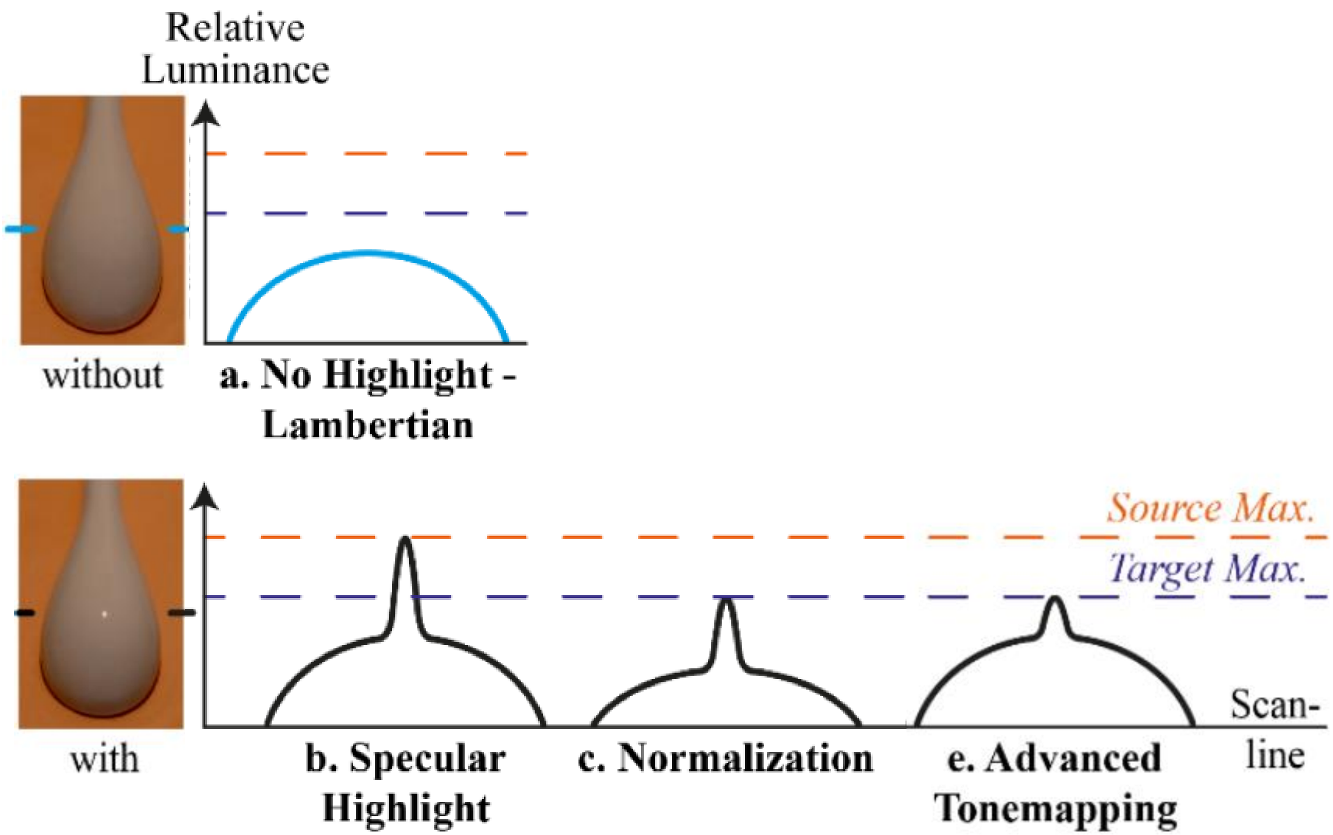


*The Perceptual Quantizer Design Considerations and Applications TIMO KUNKEL, PHD DOLBY LABORATORIES, INC. SAN FRANCISCO, CA © 2022 DOLBY ICC HDR EXPERTS DAY – MARCH 15, 2022

- **Human decisions** are necessary to fit higher dynamic range of the scenes into the standard range
- **"Reference" non linear OOTF + specifications (ITU)** are created to allow for a consistent end-to-end image reproduction

Unity slope transfer function leads to a washed-out image *(left)*
Transfer function designed to give natural feel to the image *(right)*
Courtesy of ITU BT.2390-3

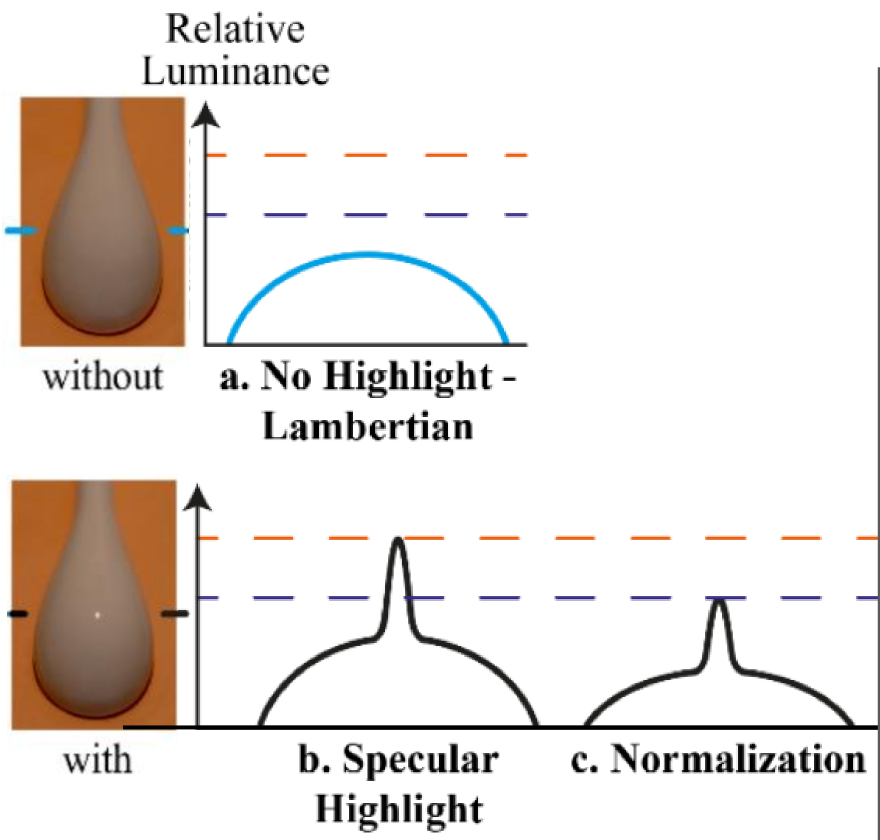
Preferred non-linear OOTF



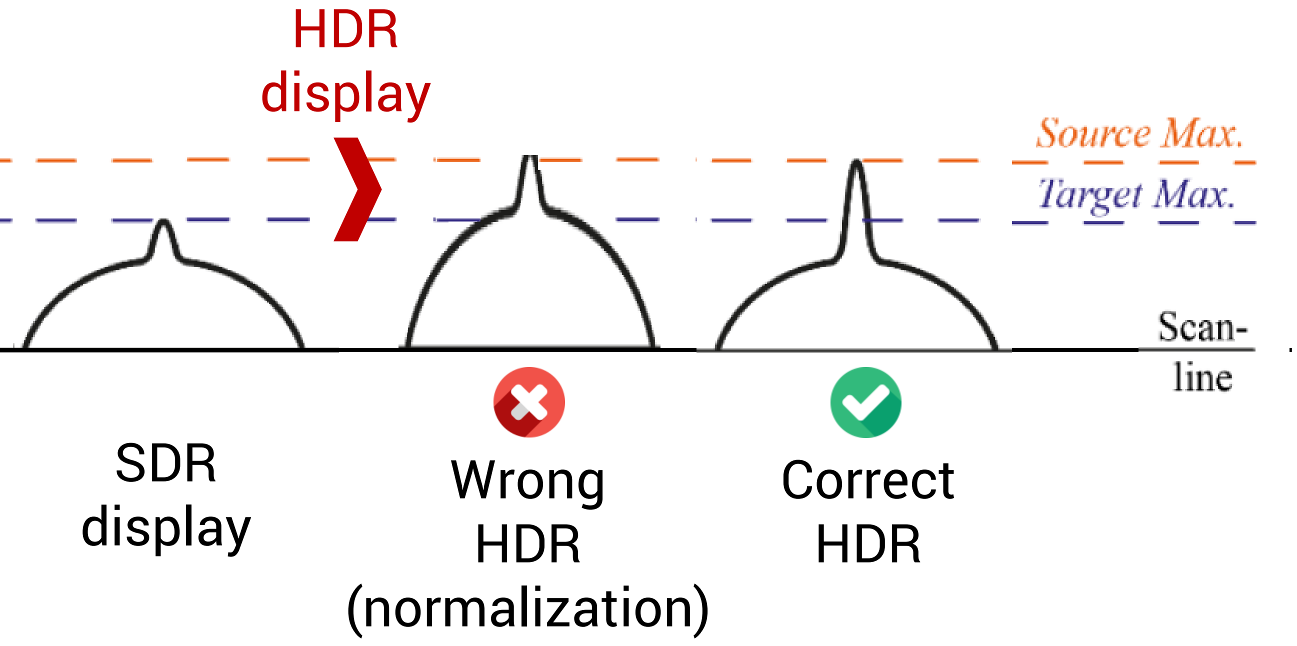
Courtesy of ITU BT.2390-3

- Rolling of the highlights is a better compromise than normalization

Preferred non-linear OOTF

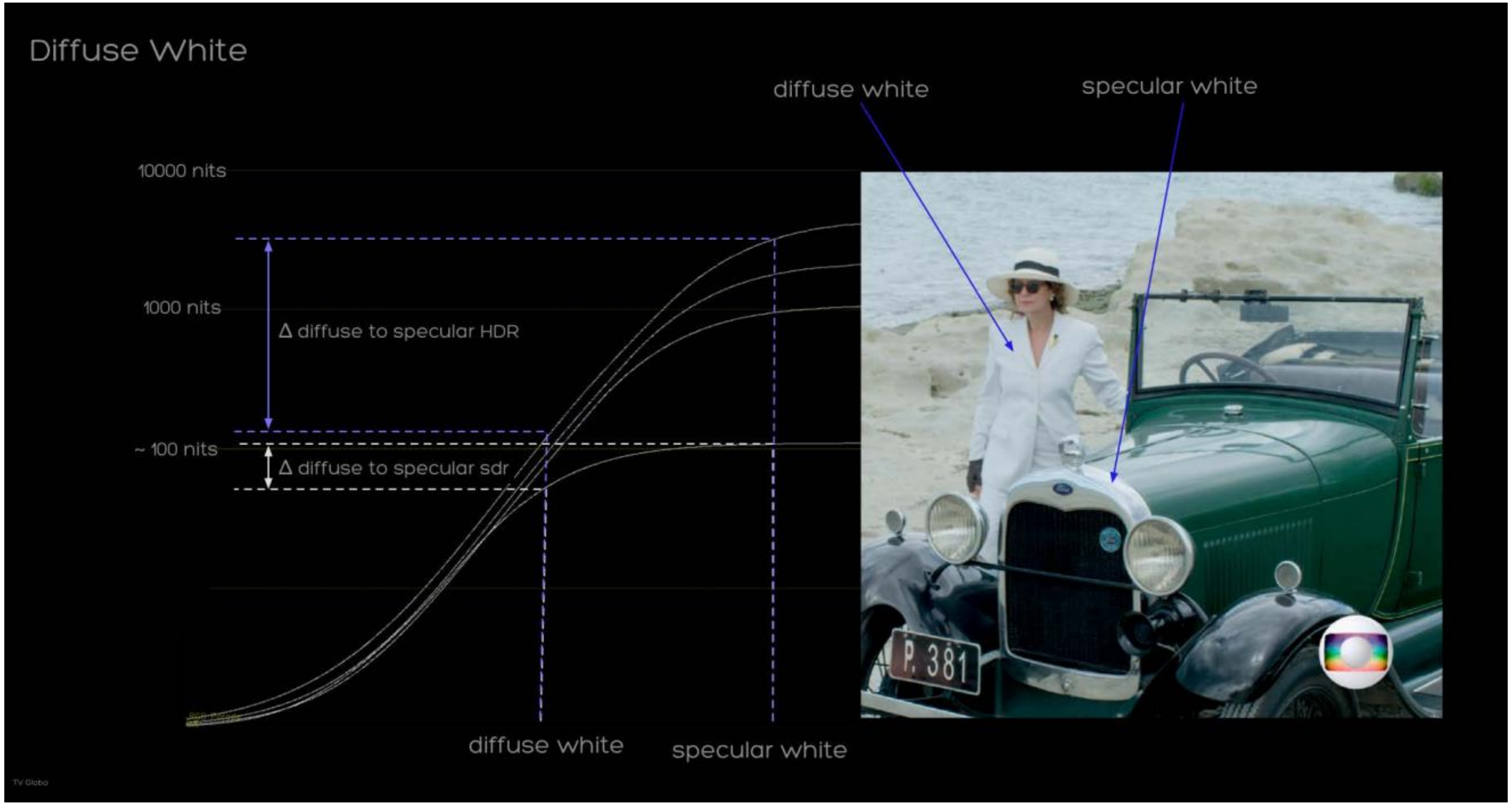


- **HDR is not brighter** : diffuse part should stay at the same level on an HDR display
- **Mostly the highlights benefits from higher dynamic range**



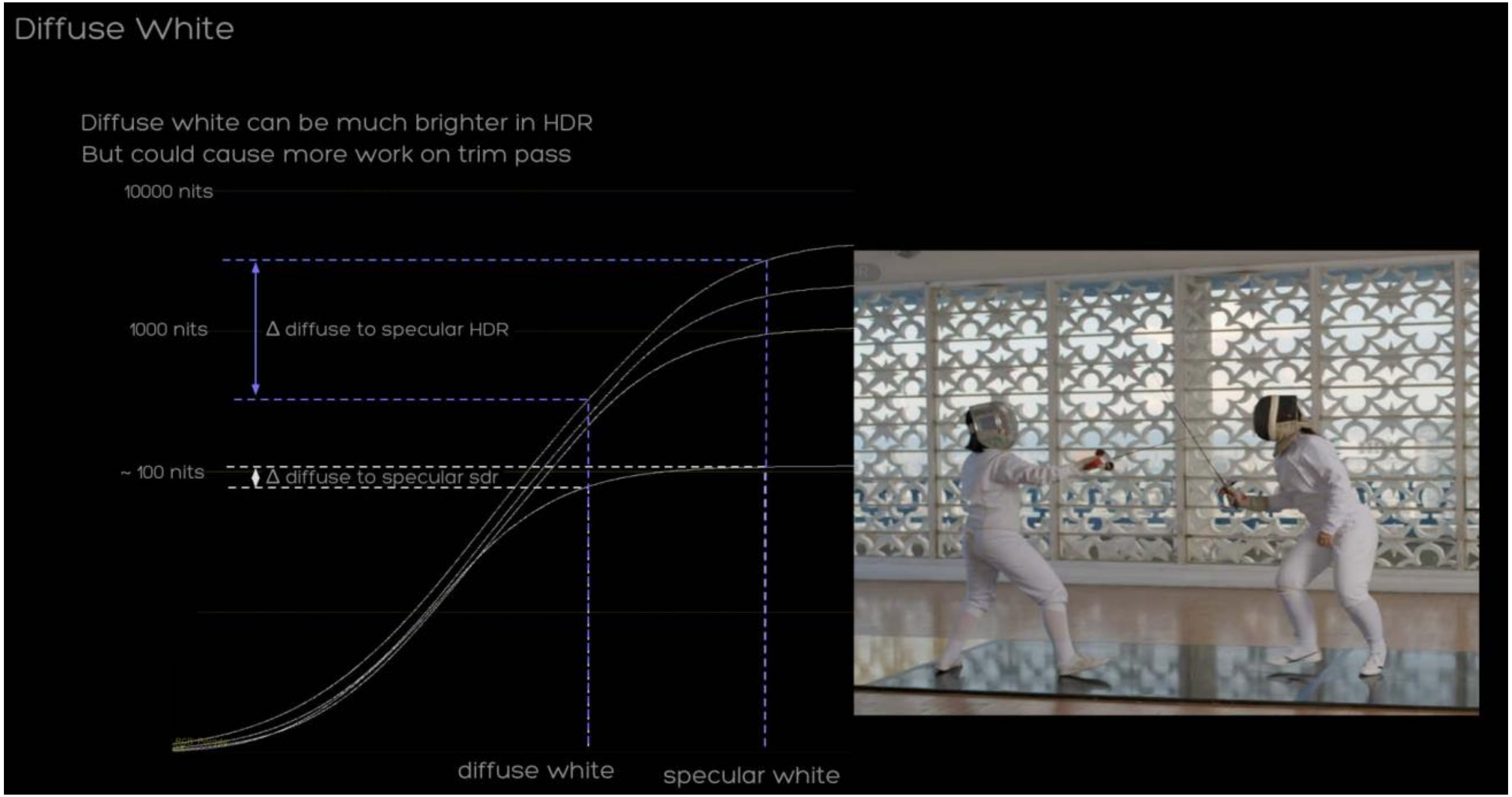
Courtesy of ITU BT.2390-3

OOTF - Diffuse White – Artistic Intent



Courtesy of Filmlight

OOTF - Diffuse White – Artistic Intent



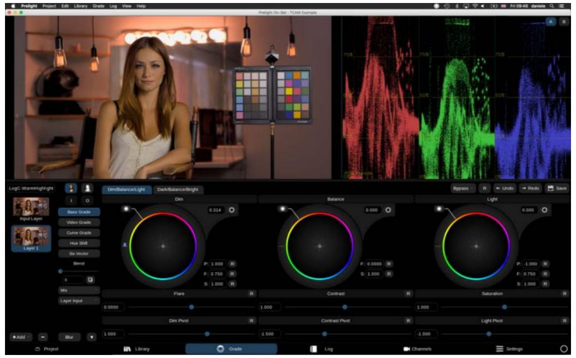
Courtesy of Filmlight

Cinema world: color / light Grading

The artistic intent is achieved in post-production by Colorist / Color grading expert (“etalonneur”) in the cinema industry.

This expertise uses tools such :
- Baselight by Filmlight
- Davinci Resolve by Black Magic

A Grading Room (Mastering displays)

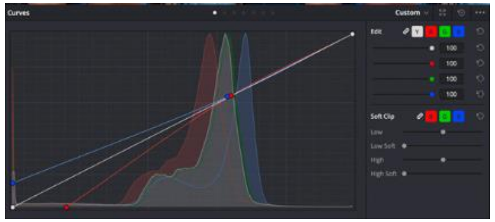


Color / Light Grading Tool Box (video/cinema)

The tool box of color grading software consists mainly of :

$$out = (i \times s + o)^p$$

- Elementary Operation per Channel : Slope Offset Power or Lift Gamma Gain
  aka “Color Decision Lists”
  →global, few parameters

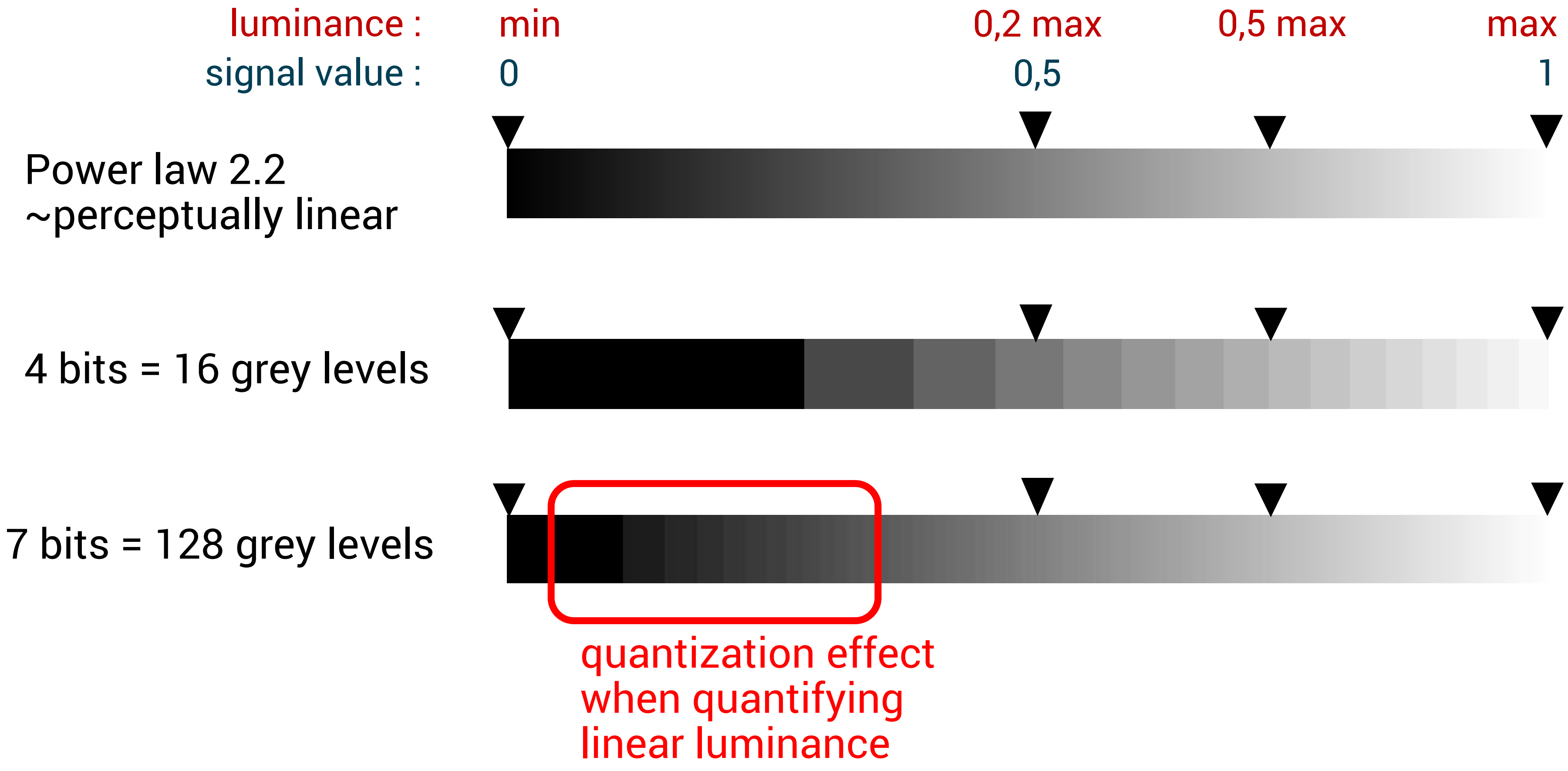


- Custom shape with control points in RGB, or HSV
  aka “Curves”
  → global, more parameters

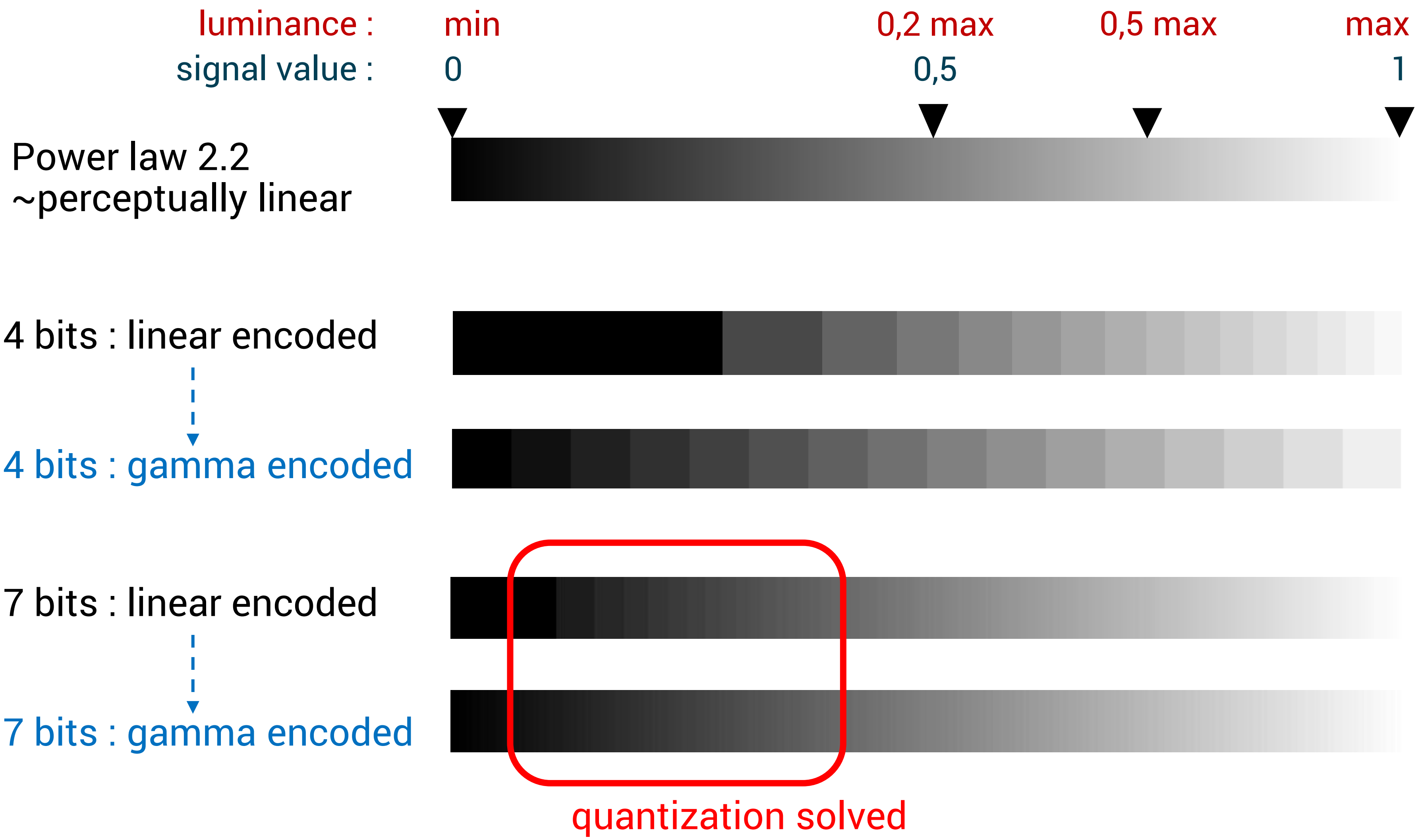
- Volume/mask selection and displacement in 3D-Scatter Plot (HSV)
  aka “secondary Curves” or “Qualifier”
  → selection unaware of geometry

- Simple Region selection, with optional tracking
  aka “Potatoes” or “U-Points”
  → intersection of geometry region and power of HSV selection

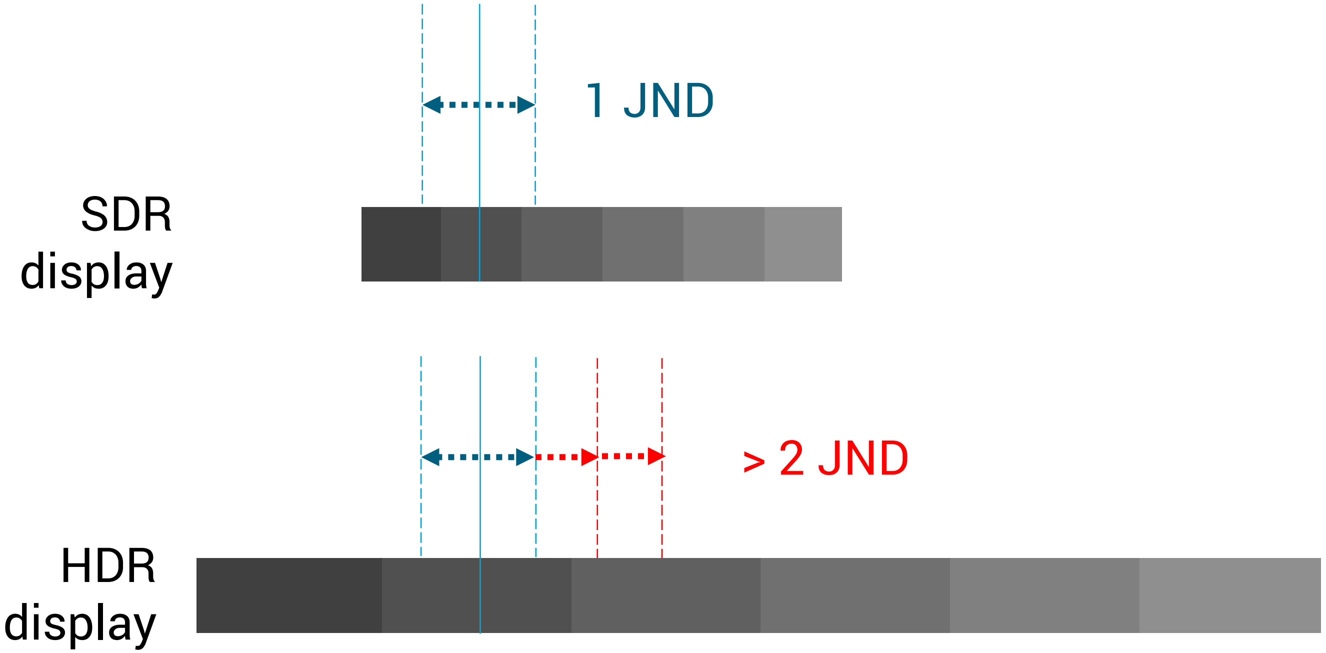
Luminance encoding : what is gamma ?



Luminance encoding : what is gamma ?



Limit of gamma



- Gamma 2.2 create **banding** on HDR displays

- Contrast between 2 grey level become higher than the **Just Noticeable Difference (JND)** between 2 level of luminance on HDR displays

… because gamma 2.2 encoding **was always sub-optimal !**

Luminance encoding beyond gamma

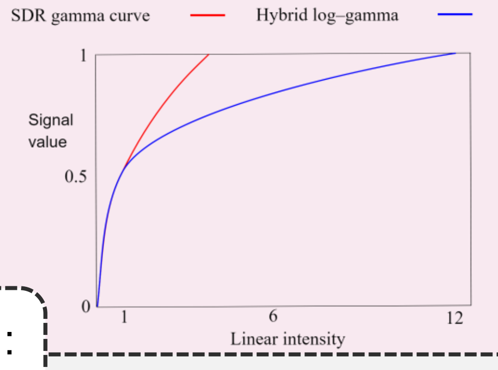
> SDR failing

HDR format

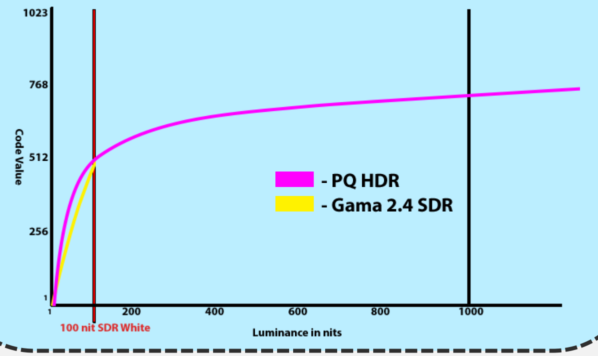
1st step :
8 bits ➔ 10 bits

2nd step :
new curve

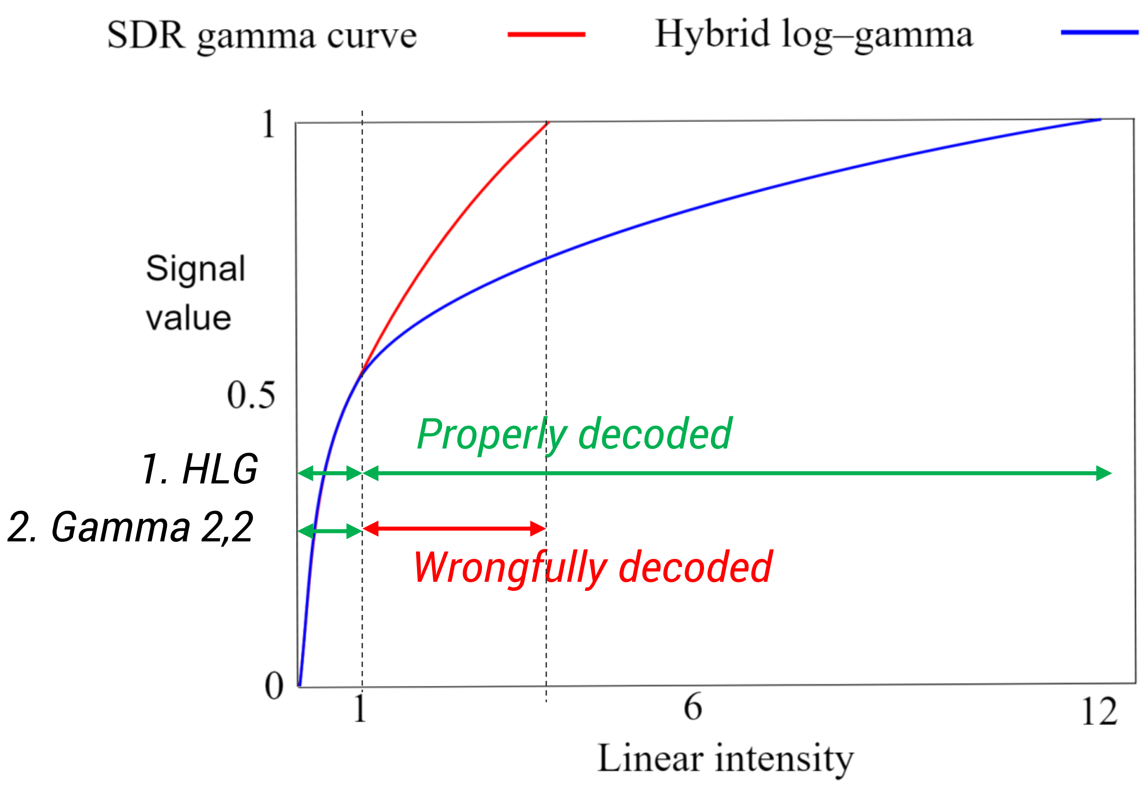
« Heuristic » solution :
HLG = hybrid log gamma curve

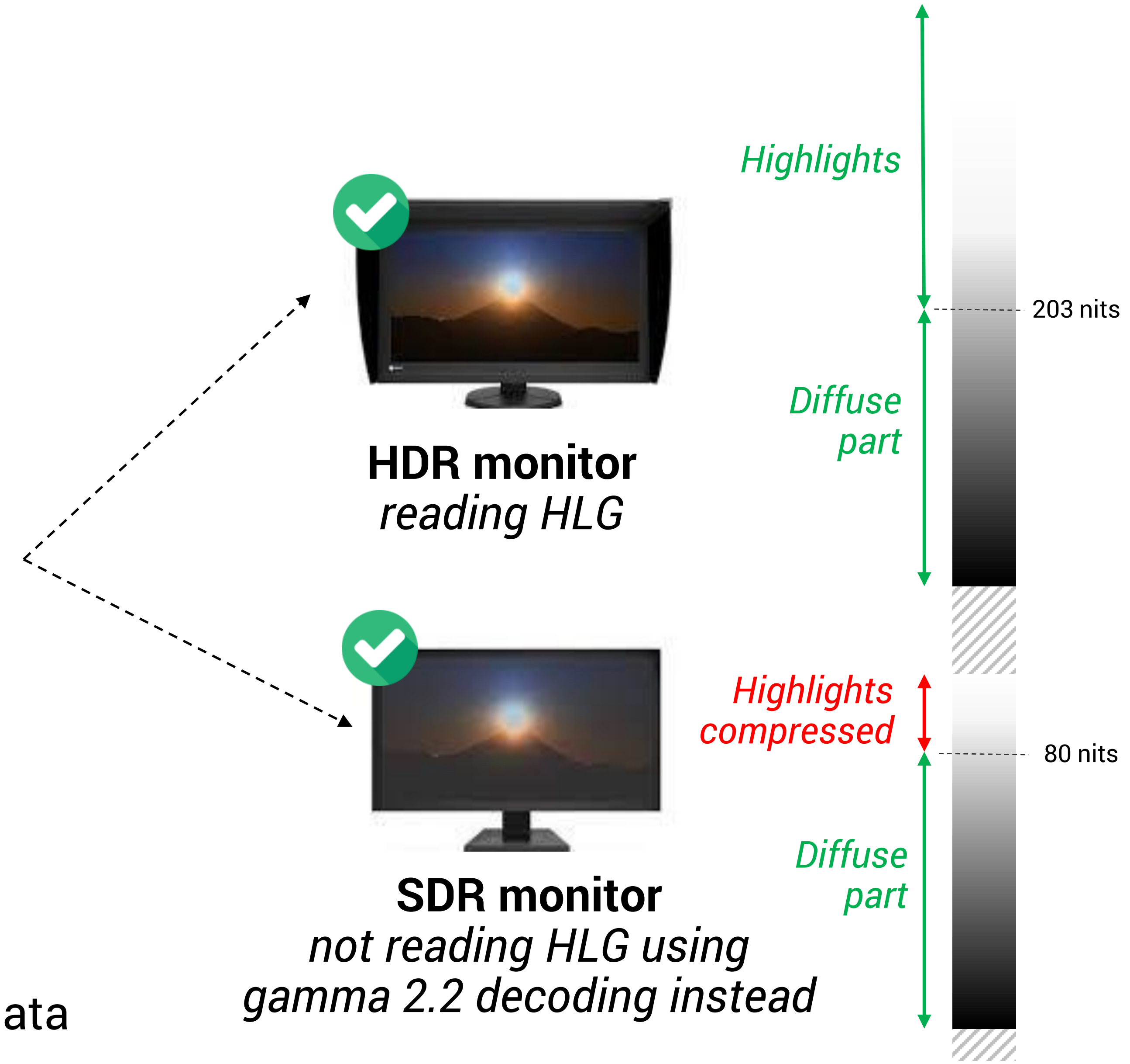


« Optimal » solution :
PQ = Perceptual quantizer



A closer look at HLG curve

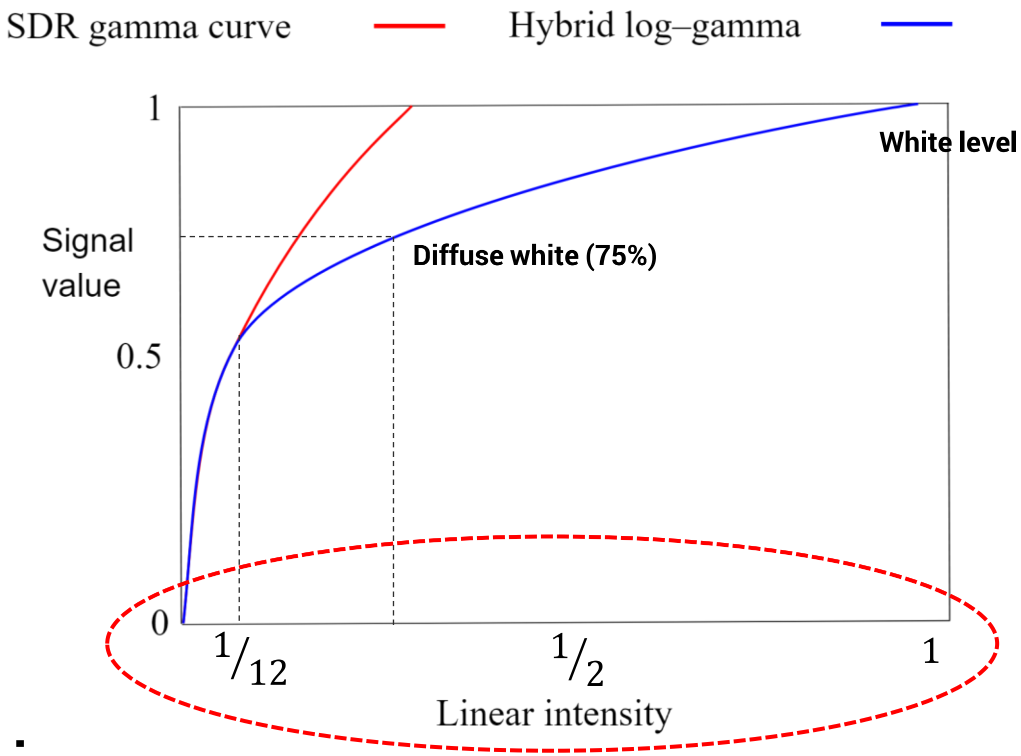




PROS :

> Great backward-compatibility + no metadata

A closer look at HLG curve : “scene” referred



PROS :

- ➢ Surrounding illuminance adaptation

CONS :

- ➢ The diffuse part might be **too low** or **too high** depending on the monitor

	White level	Diffuse white
Signal value V	1	0,75
Linear intensity E	1	0,265
Displayed luminance L (in nits)	300	80 (too low)
	1000	203
	5000	690 (too high)

OOTF (Linear intensity ⇒ Displayed luminance)

$$L \approx L_w E^{1{,}2+\log_{10}\left(\frac{L_w}{1000}\right)}$$

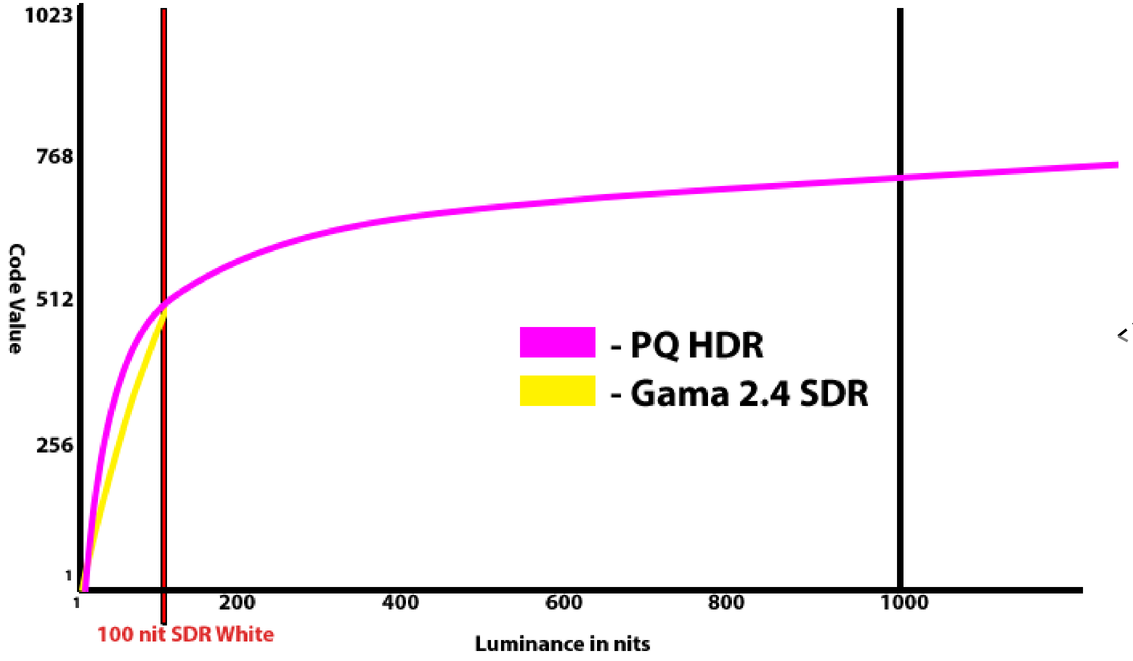
where :

- L is the displayed luminance
- L_w is the white level
- E is the linear intensity [0,1]

for :

- $L_w \gg L_B$

A closer look at PQ curve



HDR monitor
reading PQ

SDR monitor
not reading PQ using gamma 2.2 decoding instead

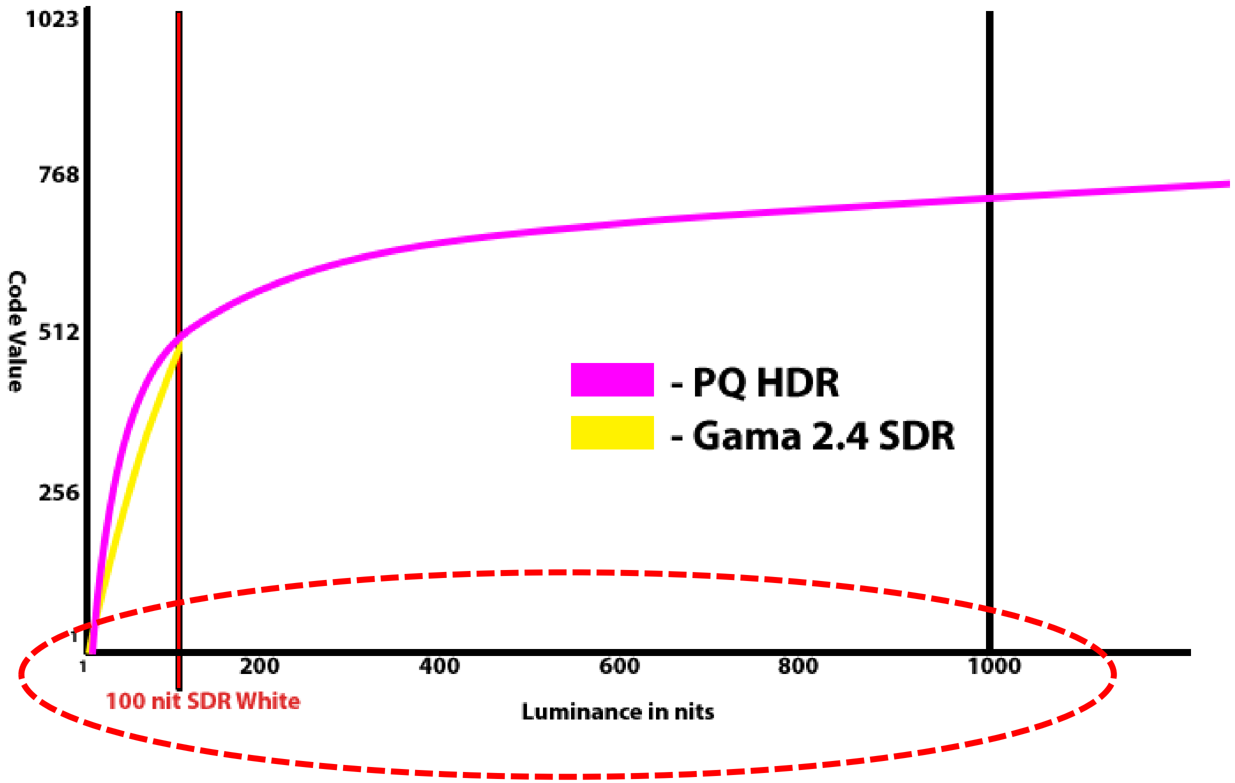
PROS :

> Future proof: no quantization up to 10 000 nits

CONS :

> Poor backward-compatibility

A closer look at PQ curve : “display” referred



PROS :

- Accurate reproduction of colorist intent WITH mastering display performances

- What if your display can’t reproduce indicated value ?

PQ vs HLG

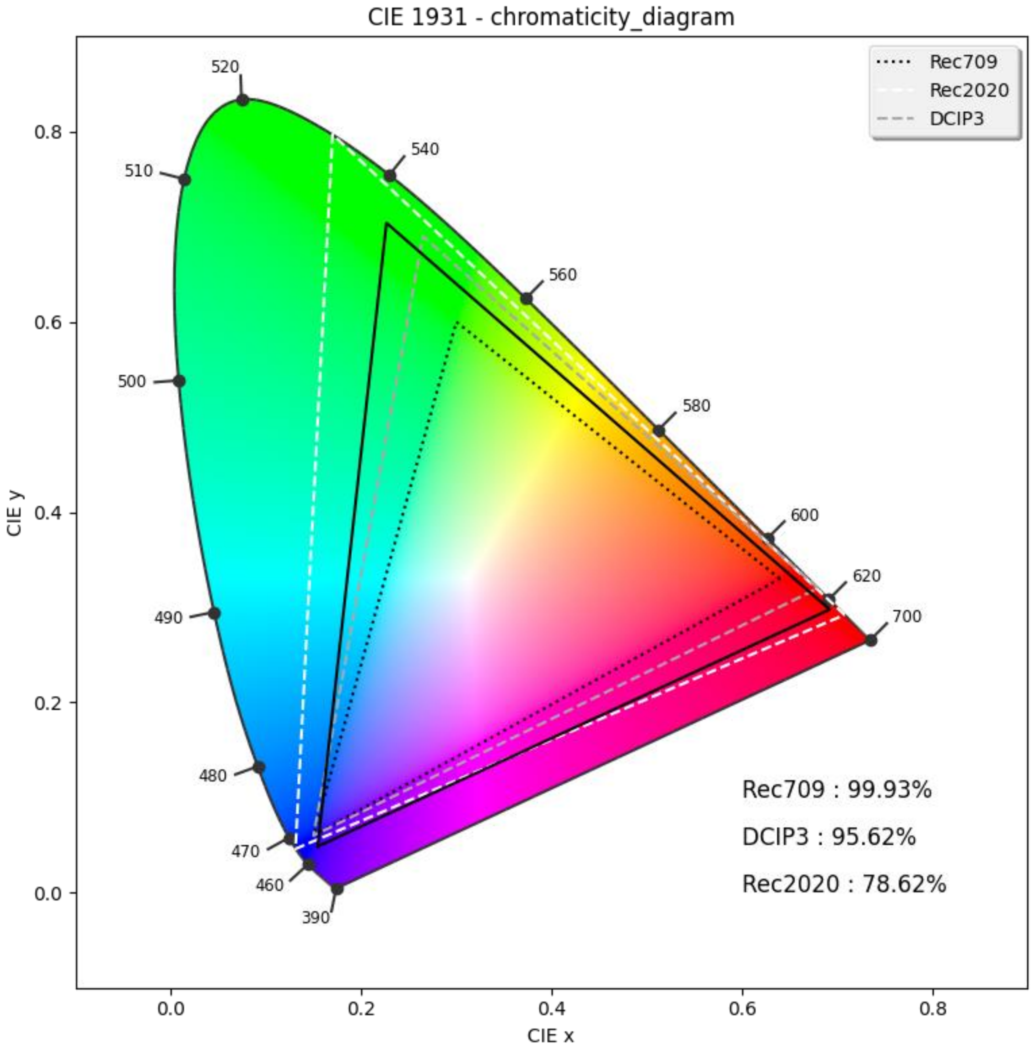
PQ is absolute.

- Define the relation between gray levels and light out of the display in cd/m²
- Requires a well control viewing environment: 40° FOV, 5cd/m² Surround.
- Designed for Cinema, by the cinema industry (Dolby)
- If read by a playback system unaware of HDR : results is visibly wrong.

HLG is relative.

- Define the relation between gray levels and level relative to display peak (in %)
- Supposed to be more robust to viewing conditions (surround should be 10% of peak display)
  - HLG has an EOTF modifier which introduce a slight gamma to adapt to the surround
- Design for TV/Broadcast, by TV Broadcast industry (NHK /BBC)
- If read by a playback system unaware of HDR : results if not so wrong on low to mid tones…

RGB color spaces for HDR

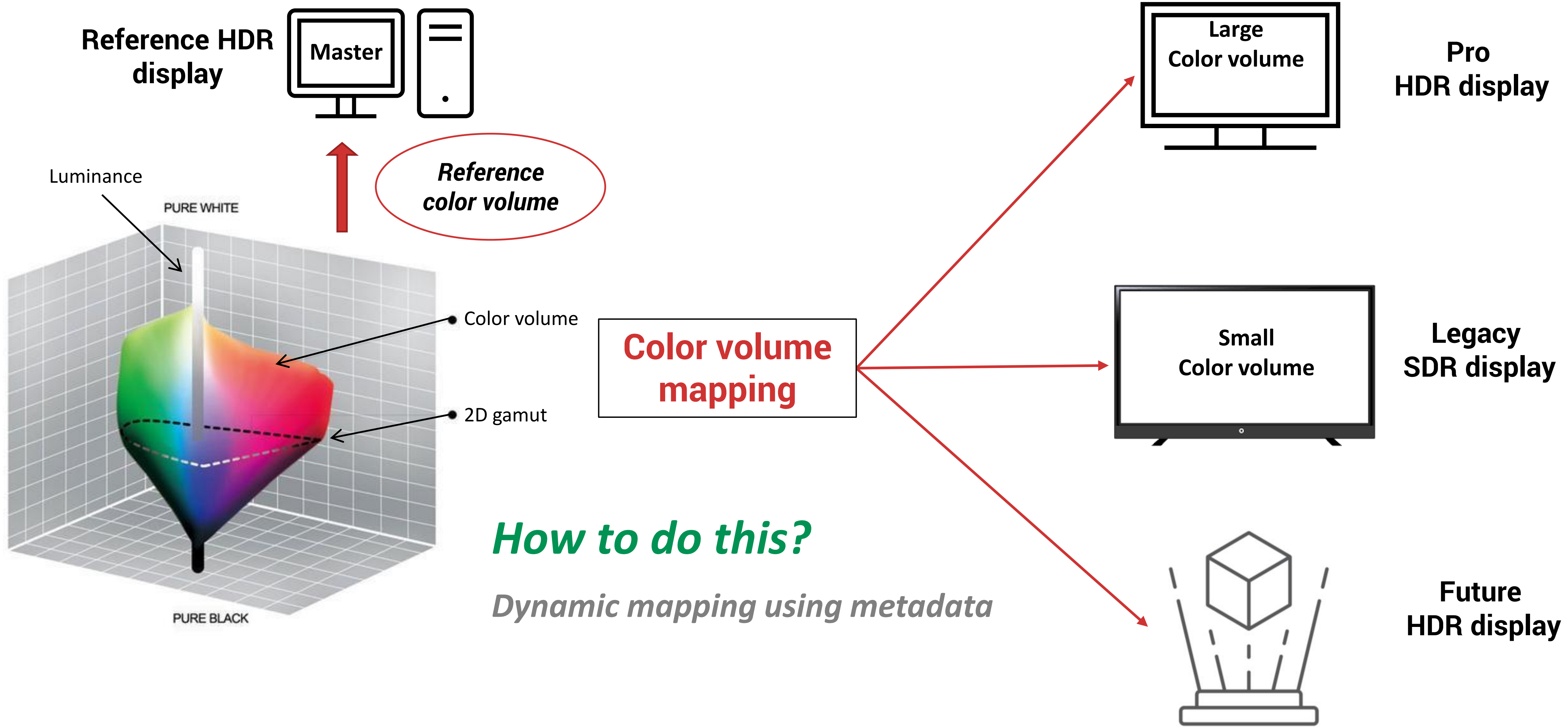


- ➢ HDR displays are also capable of displaying **wider color gamuts** (WCG)
- ➢ **BT.2020** became the reference RGB color space for HDR format since most can cover full DCI-P3
- ➢ Issue of **gamut-mapping**

Delivering the potential

Adaptation to the display capabilities, Adaptation to the viewing conditions

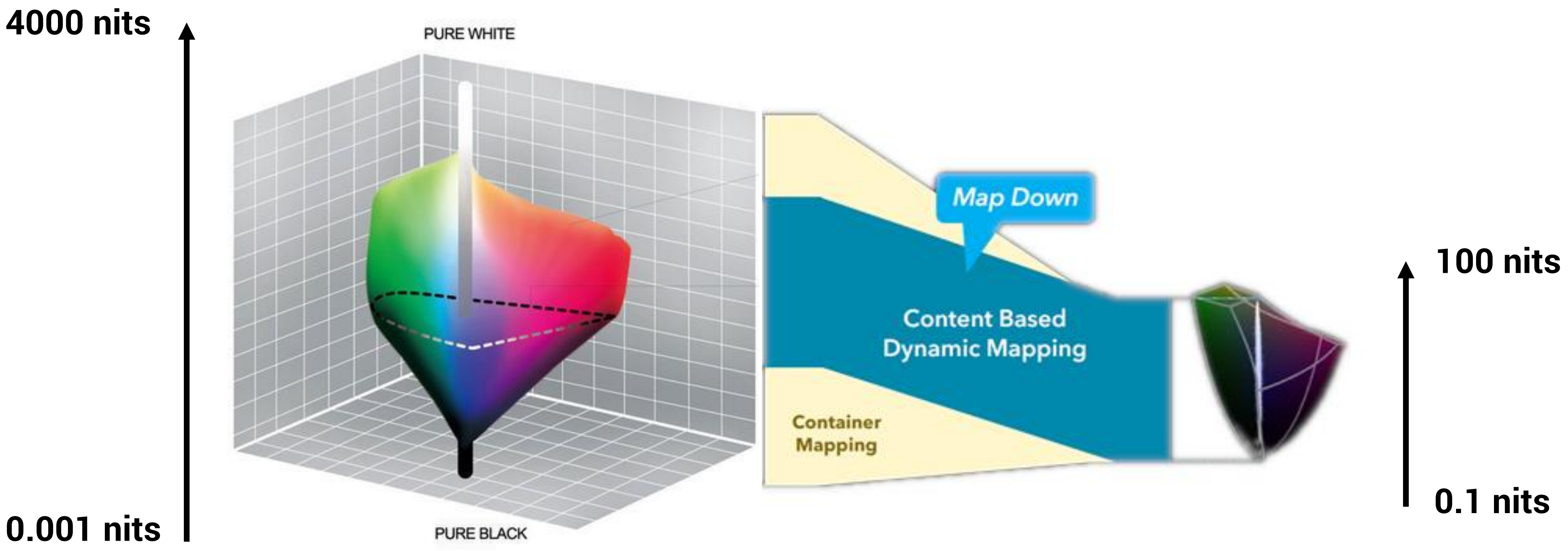
The challenge – Delivering the potential



How to do this?

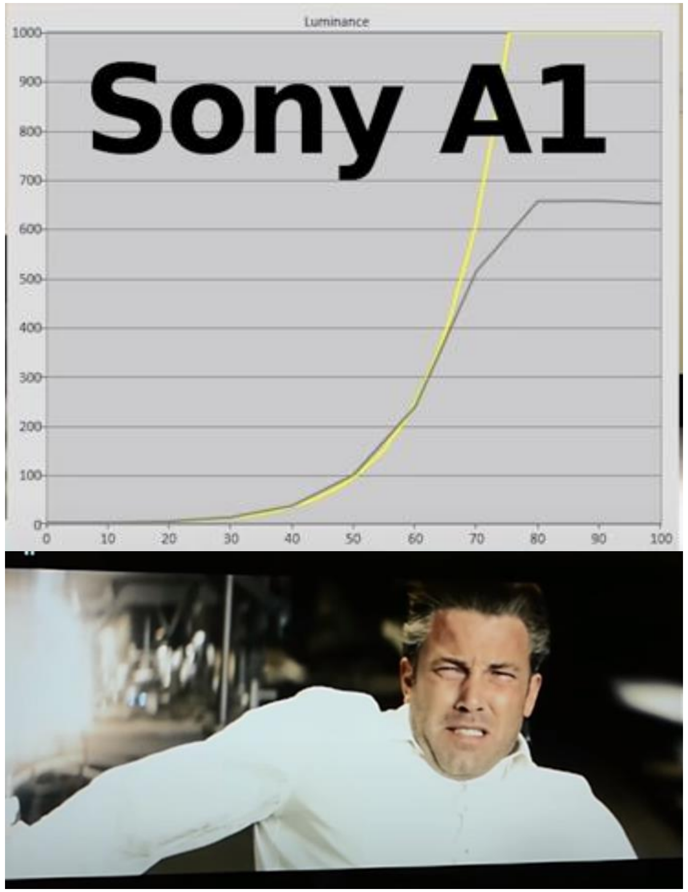
Dynamic mapping using metadata

Dynamic mapping using metadata



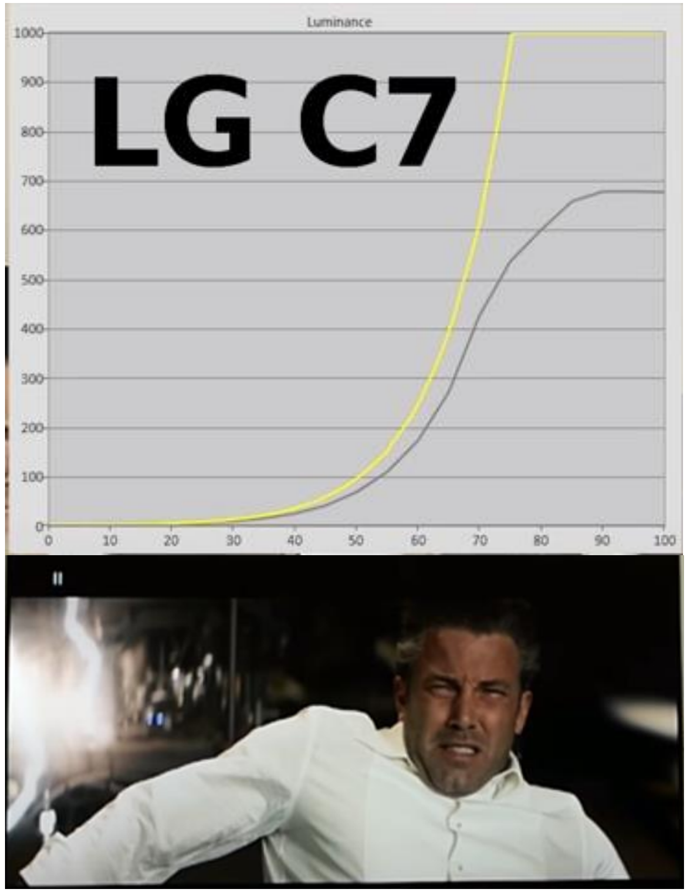
Tone-mapping on Display side

- **Clipping**



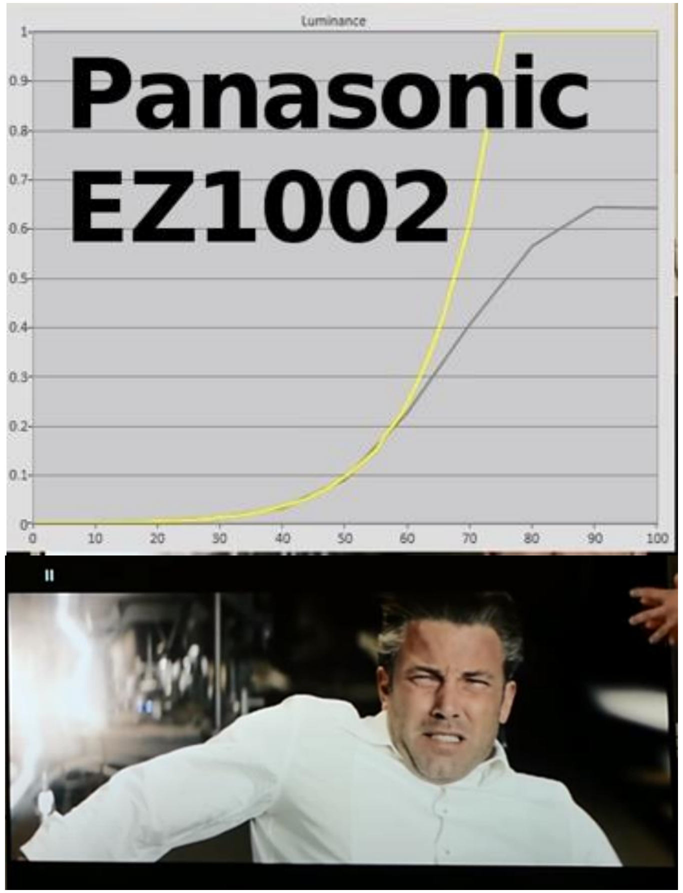
… loss of highlight details

- **Global roll-off**



… underexposed globally

- **Highlight roll-off**



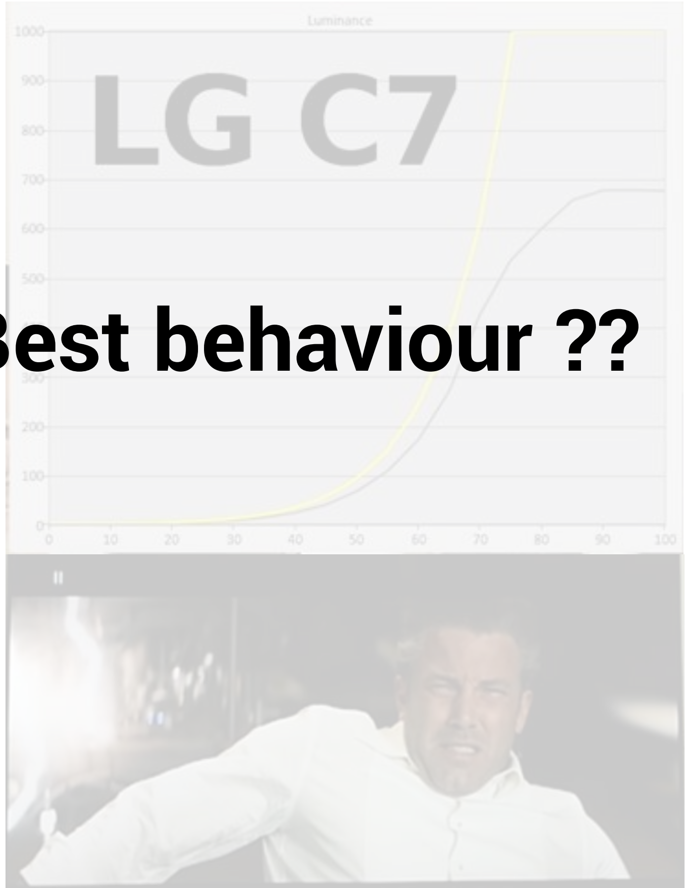
compromise

Tone-mapping

- Clipping

… loss of highlight details

- Global roll-off



… underexposed globally

- Highlight roll-off

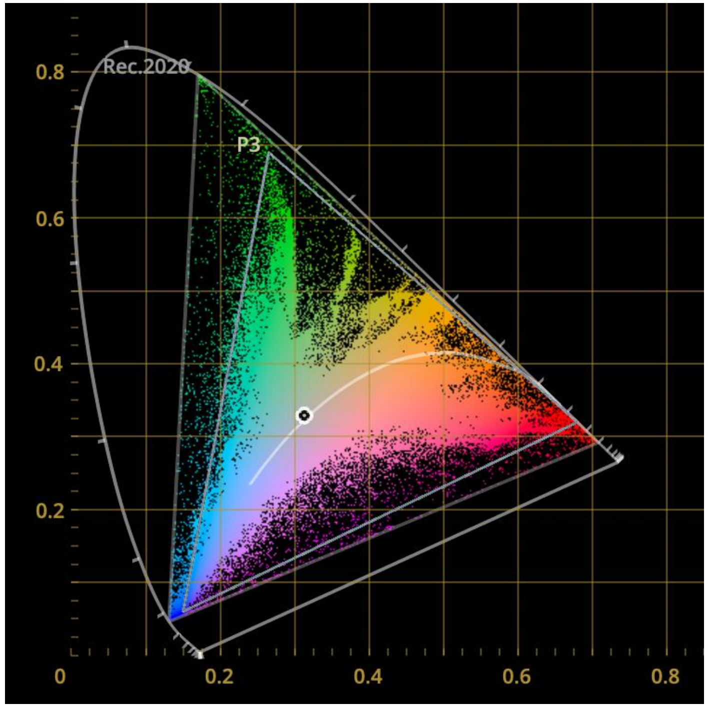
compromise

Best behaviour ??

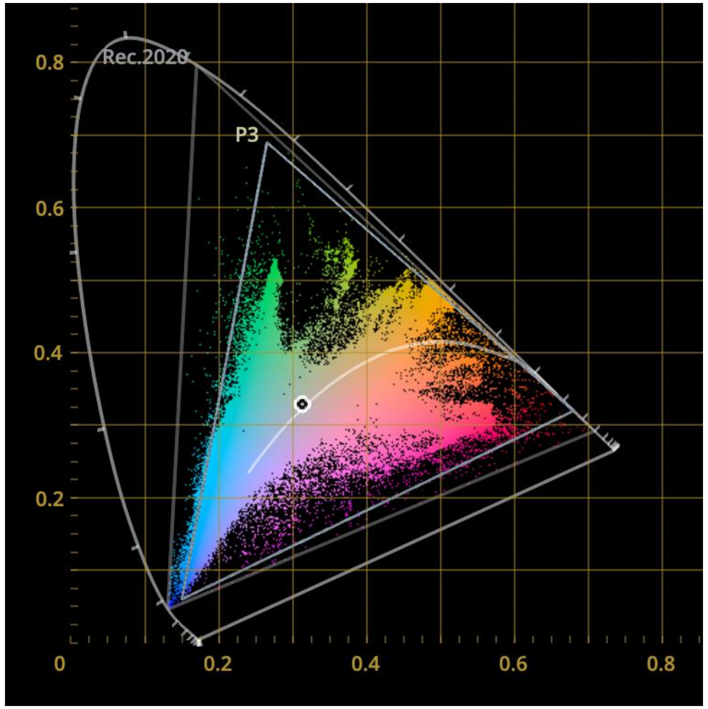
Impact of WCG on users

- Iphone 13 Pro Max HDR videos of DMC :

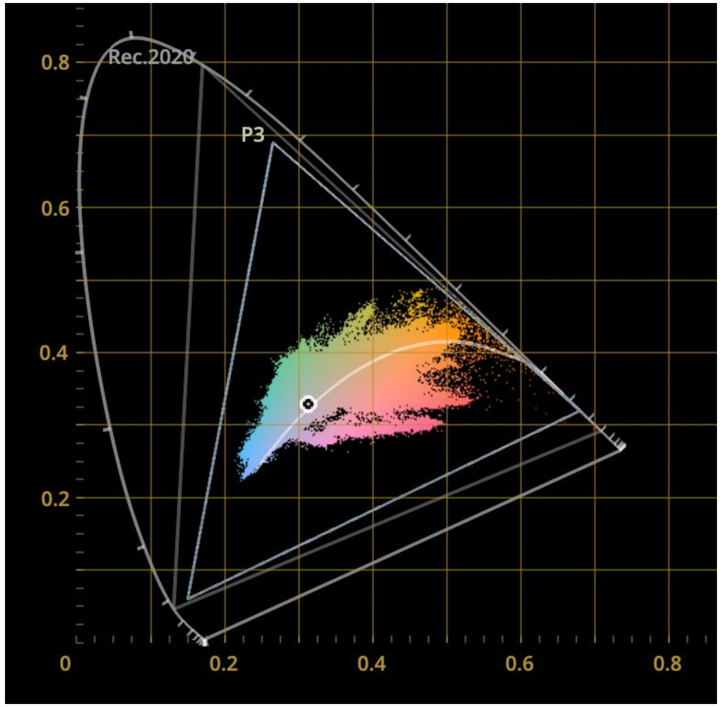
1000 lux



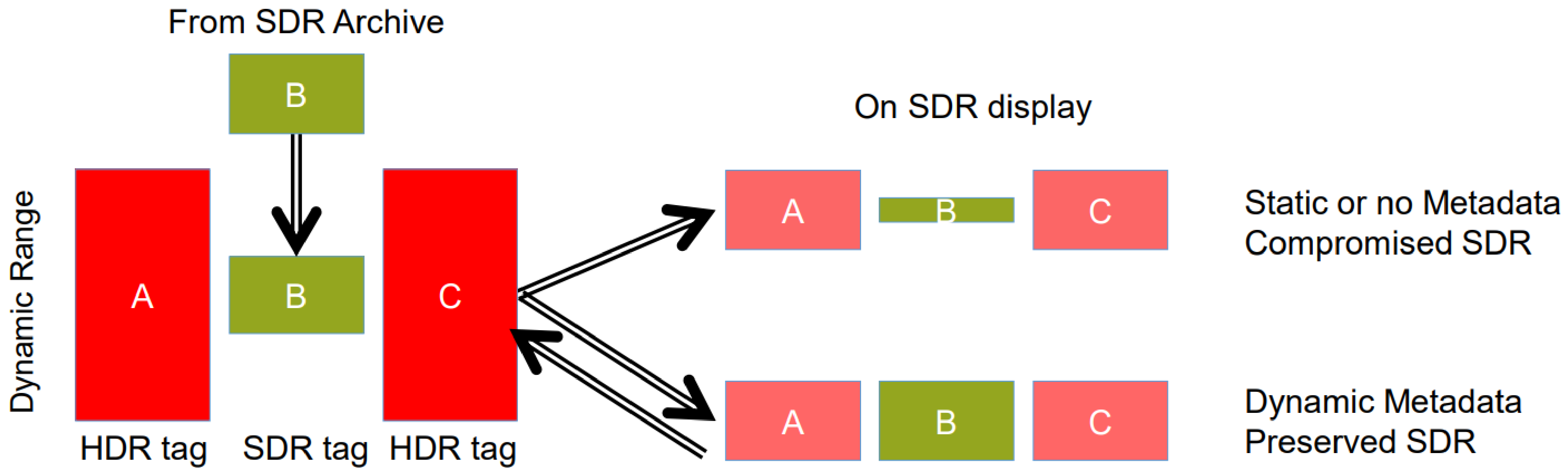
300 lux



20 lux

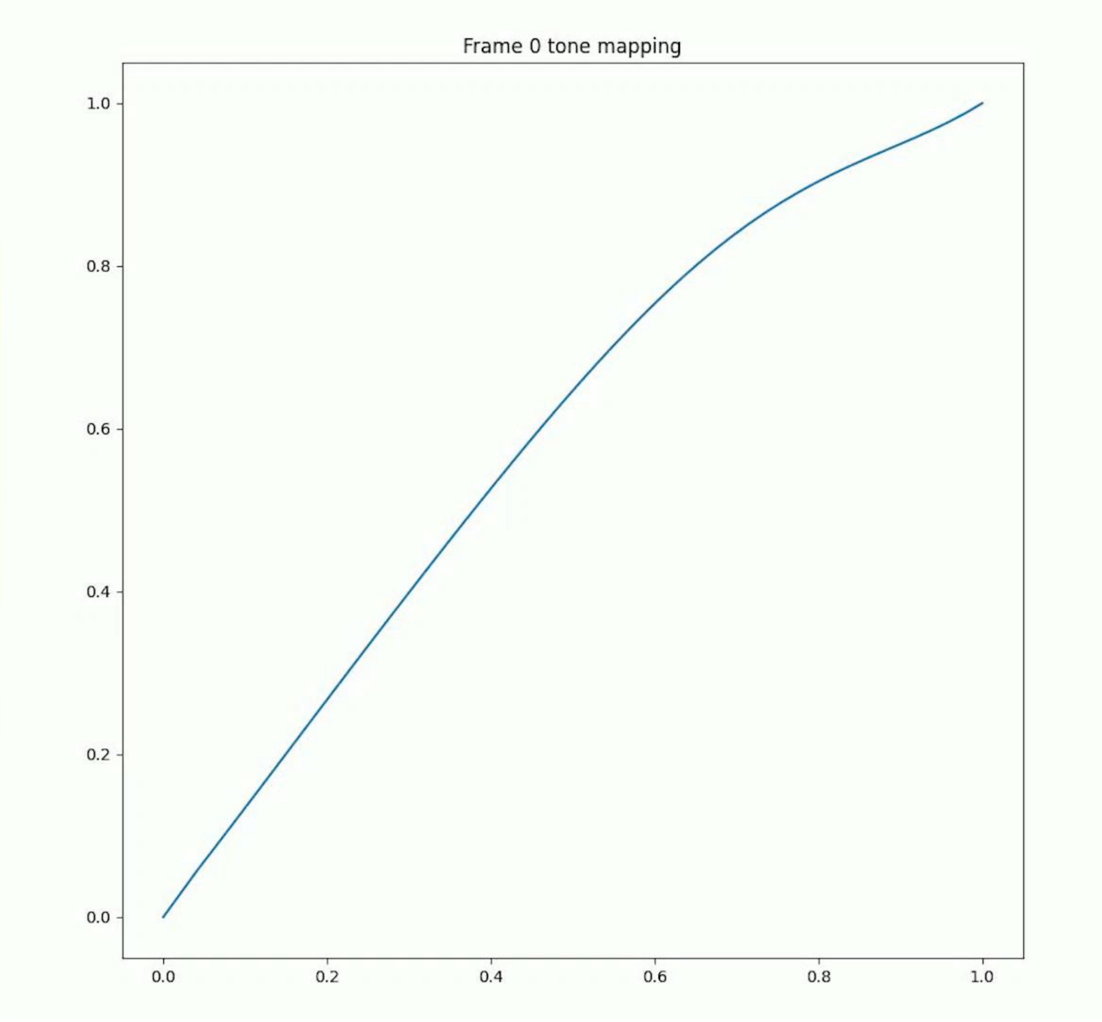


Dynamic metadata : temporal adaptation



Dynamic metadata : frame-by-frame tone mapping

HDR10+
video shot
on Samsung
S22 Exynos



Main HDR formats available

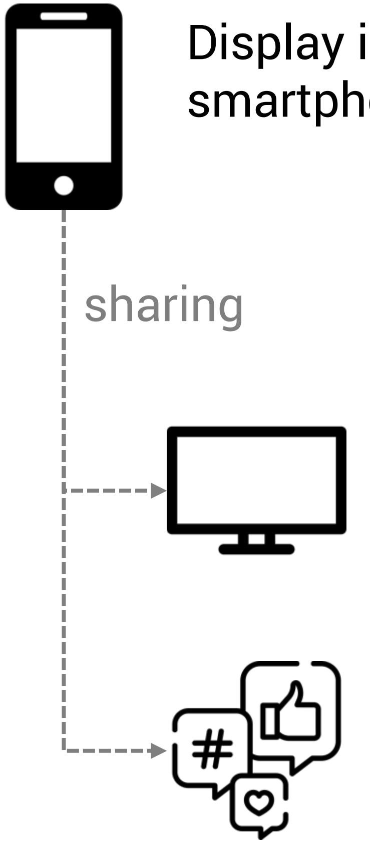
FORMAT	TF	Static metadata	Dynamic metadata	Backward compatibility		Support	LICENSE
				No metadata handling	Metadata handling		
HDR10	**PQ**	YES	NO	NO	NO	ALL HDR DEVICE	OPEN
HLG10	HLG	NO	NO	YES		ALL HDR DEVICE	OPEN
DOLBY VISION	**PQ**	NO	YES	NO (=HDR10)	YES	MOST HDR TV, MOST HDR MONITORS	ROYALTIES
	HLG	NO	YES	YES	YES		
HDR10+	**PQ**	YES	YES	NO (=HDR10)	YES	RECENT HDR TV, NO MONITORS	ANNUAL FEES
VIVID HDR	**PQ**	YES	YES	NO (=HDR10)	YES	RECENT CHINESE TV, NO MONITORS	OPEN ? ANNUAL FEES ?
	HLG	YES	YES	YES	YES		

Oldest to newest format

Smartphone manufacturers

FORMAT	TF	MANUFACTURER
HDR10	**PQ**	
HLG10	HLG	
DOLBY VISION	**PQ**	
	HLG	APPLE, XIAOMI
HDR10+	**PQ**	SAMSUNG, XIAOMI, GOOGLE
VIVID HDR	**PQ**	
	HLG	HUAWEI

From a user point of view :



Display is HDR for high-end smartphone

PQ : recent smart TVs
HLG : all tv, all monitors

Youtube support, instagram support coming …

HDR Photo

Fresh News

ISO 22028-5 - High Dynamic Range and Wide Colour Gamut encoding for still images

2020:
Apple introduce HDR photography

2022:
Apple and Adobe pushes HDR format for still photography.

2023:
Google launches UltraHDR, compatible with -5.

Metadata are inspired from the HDR Video

- PQ or HLG EOTF
- P3-D65 Color space (≠Rec 2020)

The standard describe reference viewing display:
Peak 1000 nits / Blacks 0.0005 nits / P3-D65
Default diffuse white 203 nits.

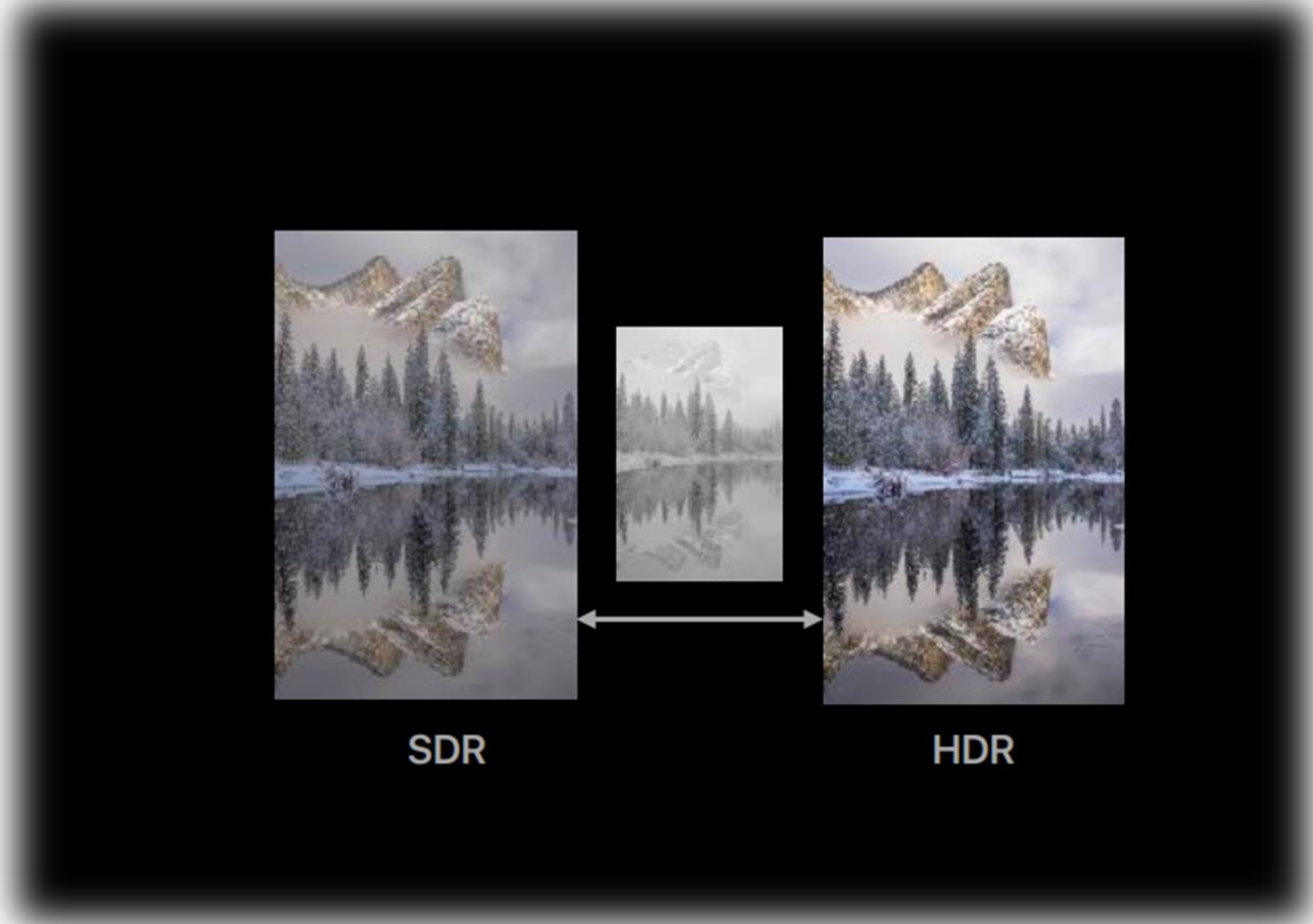
Gain Map

2023:
Apple and Adobe introduce metadata to be added to a photo file to switch between SDR and HDR rendering.

Google support GainMap in their UltraHDR format (Pixel 8 + Android + Chrome!)

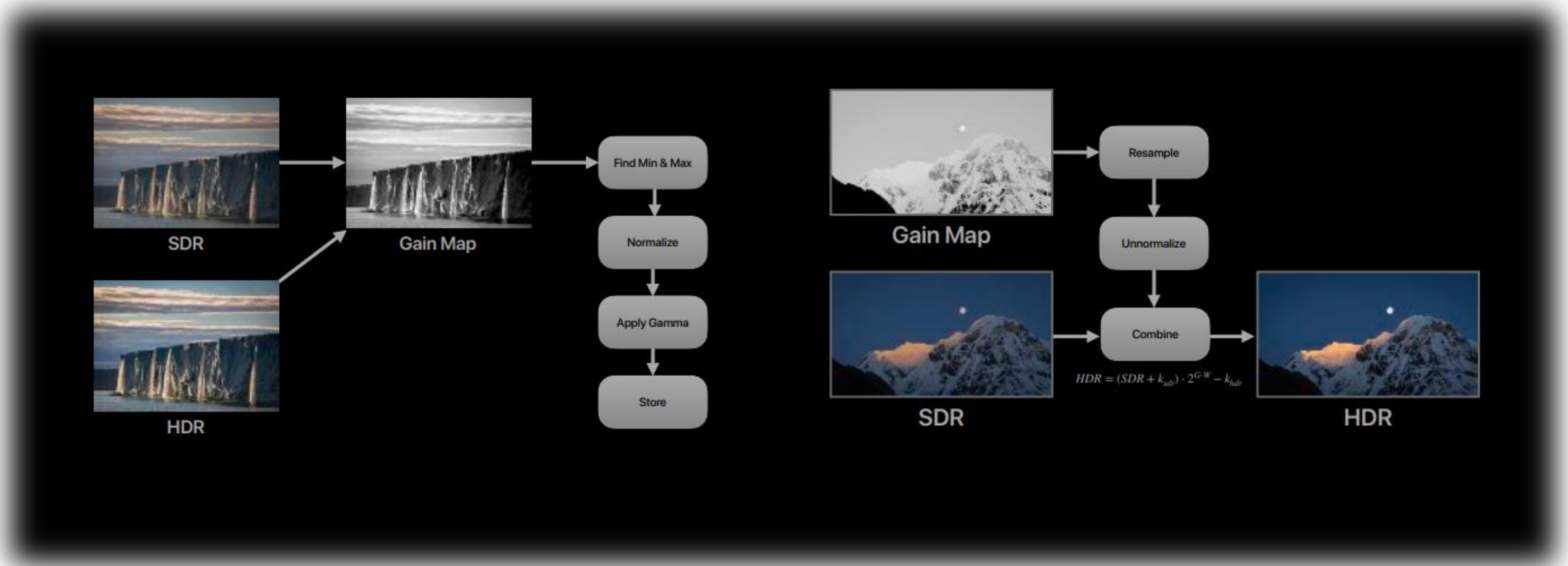
$$G = log_2\left(\frac{HDR + k_{hdr}}{SDR + k_{sdr}}\right)$$

The gain map is expressed in stops.
It is applied in the linear domain.



The metadata can be added to a SDR file to produce a HDR rendering (transition while reader do not understand metadata)
The metadata can be added to a HDR file to produce a SDR rendering (back compatibility for SDR screen when reader will understand metadata)

Gain Map Storage



The size of of the gain map should be lower than a secondary version of the image...

Gain Map

Adobe suggests an algorithm to interpolate between SDR and HDR renderings.
This can be used to:

- adapt to the actual capacity of the screen, if this one is not conform to the mastering display
- Adapt to the viewing conditions if they are different from the reference ones.

```
vec3 ApplyGainMap (image2d baseImage,
                   image2d gainMap,
                   vec2 position,
                   float w,          // weight for applying the gain map
                   vec3 gainMapMin,  // from gain map metadata
                   vec3 gainMapMax,  // from gain map metadata
                   vec3 gainMapGamma, // from gain map metadata
                   vec3 offsetBase,  // from gain map metadata
                   vec3 offsetOther) // from gain map metadata
{
    vec3 base = ReadImage (baseImage, position);

    vec3 gainMapEncoded = ReadImage (gainMap, position);

    vec3 gainMapLog2 = lerp (gainMapMin,
                             gainMapMax,
                             pow (gainMapEncoded, vec3 (1.0) / gainMapGamma));

    return ((base + offsetBase) * exp2 (gainMapLog2 * w)) - offsetOther;

}
```

$$HDR_{capacity} = log_2\left(\frac{HDR_{white}}{SDR_{white}}\right)$$

$$F = \text{clamp}\left(\frac{HDR_{capacity} - HDR_{min}}{HDR_{max} - HDR_{min}}, 0, 1\right)$$

$W = F$ if Base is SDR

$W = F - 1$ if Base is HDR

Challenges for Image Quality

White point, Color Space, Perception

Different approaches of HDR pipelines

- Cinema / Professionnal Photography:
  - Color Grading → Many hours of manual / Visual tuning
  - Target is artistic intent
- TV / Broadcast :
  - “Real time Color Grading” → Normalized Guidelines, IUT Recommendation
  - Target is uniformity
- All In One Cameras / Smartphone :
  - Everything is automatic, using computational means / machine learning…
  - Target is …quite open… a mix between the two ?

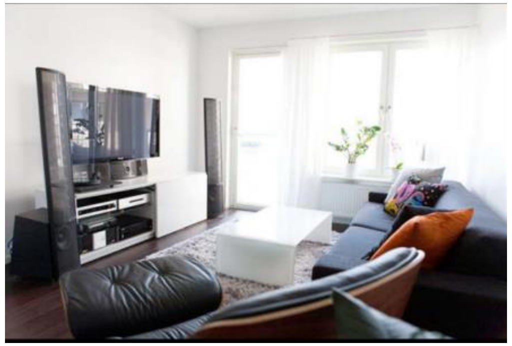
Viewing / Playback Conditions are important to take into account to estimate image quality

Reference: Master Display / Mastering Viewing Conditions:

- Great Peak White
- Great Blacks
- Great Color Gammut
- 5Lux Dim Surround

Is it the final use case?

Your TV in your living room:
- Not so great peak white
- Not so great blacks
- Not so great color gammut
- Changing surround



Reflection ~ 5% (AR only)

Smartphone are mobile display:
- Ambiant conditions varies from outdoor to lowlight..
- Reflection
- Field of View
- Eye glare
- The device adapts to it

Viewing / Playback Conditions

Image quality perception is much more sensitive to viewing conditions :
- state of adaptation
- 2nd order parameters of HVS

FIGURE 1

Black level detectability as a function of duration for different initial adaptation levels. From Stokkerman [6]

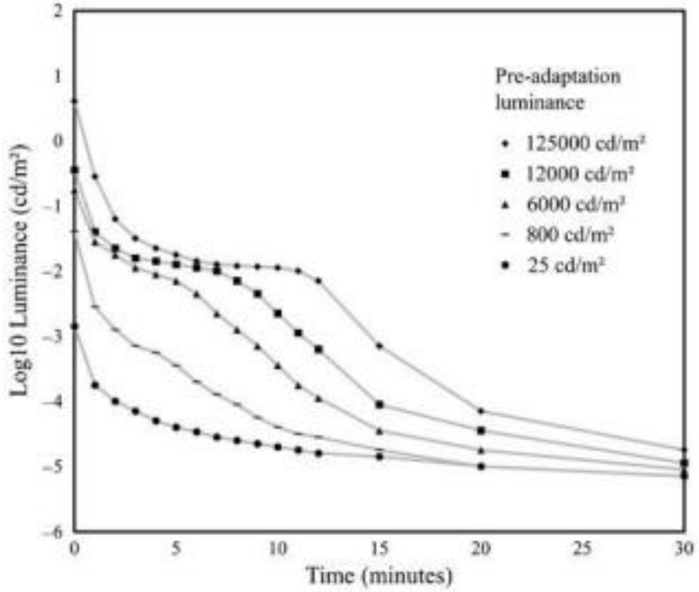
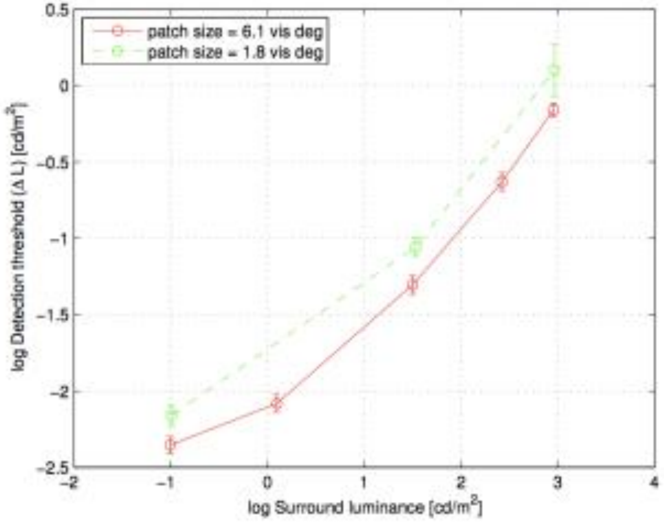


FIGURE 2

Detectability of black level differences for a rectangular patch of either 6.1 or 1.8 visual degrees, both as a function of surround luminance level



Courtesy of ITU BT.2390-3

Objective Measurements challenge

Color science is mostly based on White diffuse point.

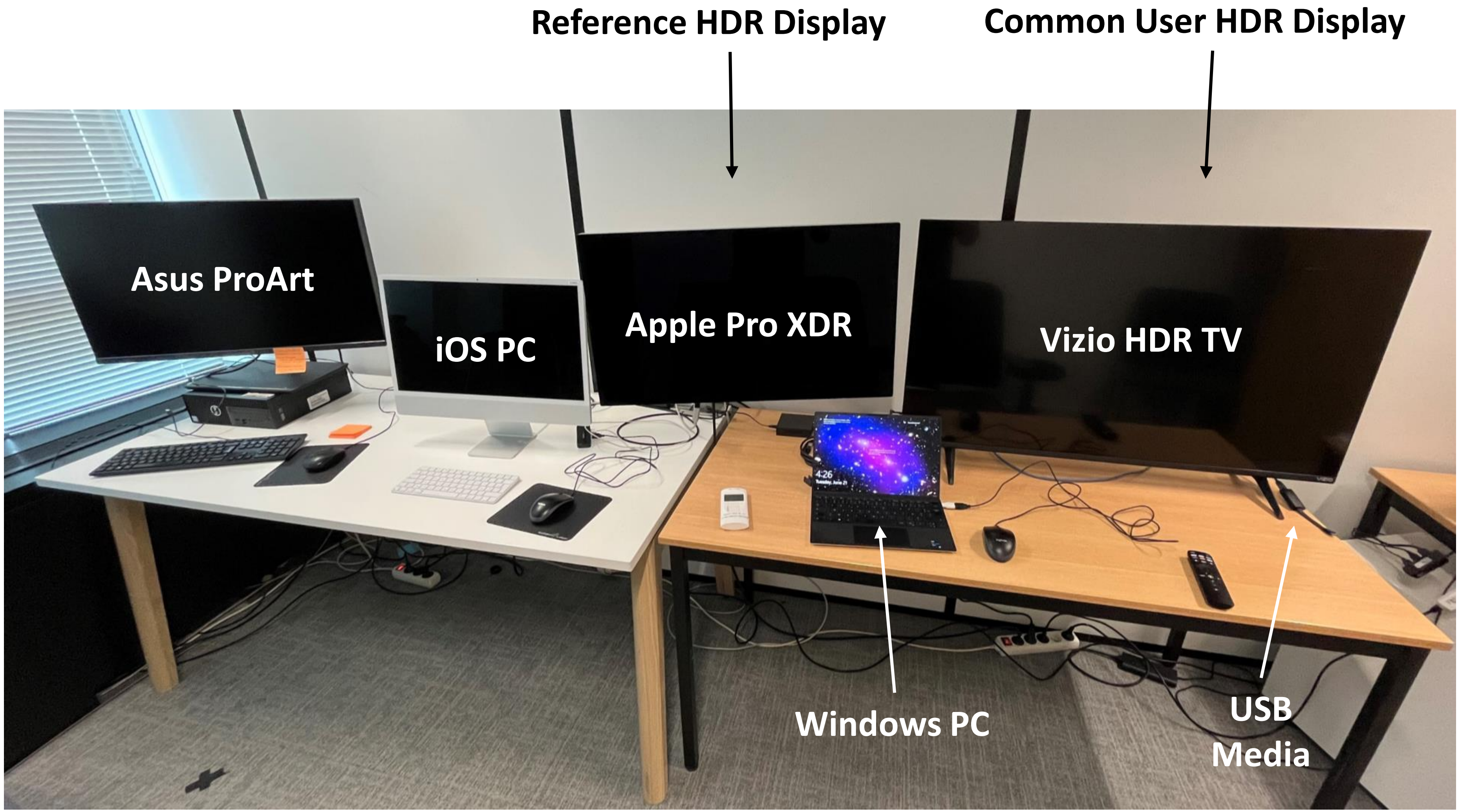
- Perceptual color space such as CIE Lab are originally designed to support a dynamic range of approximately 100:1
- Design of color space that works at luminance level order of magnitude above and below white point.

HDR-CIELAB, CIECAM16-UCS

$$L_{hdr}, a_{hdr}, b_{hdr} = F(X, Y, Z, X_{wp}, Y_{wp}, Z_{wp}, Y_s, Y_{abs} , ...)$$

Y_s : relative luminance of the surround
Y_{abs} absolute luminance
… State of adaptation

HDR Format – for capture evaluation – HDR Visualization Room



1. Asus ProArt
   - The monitor is HDR compatible, and it has been calibrated to Rec2020 HDR-PQ and DCI-P3 gamma 2.2

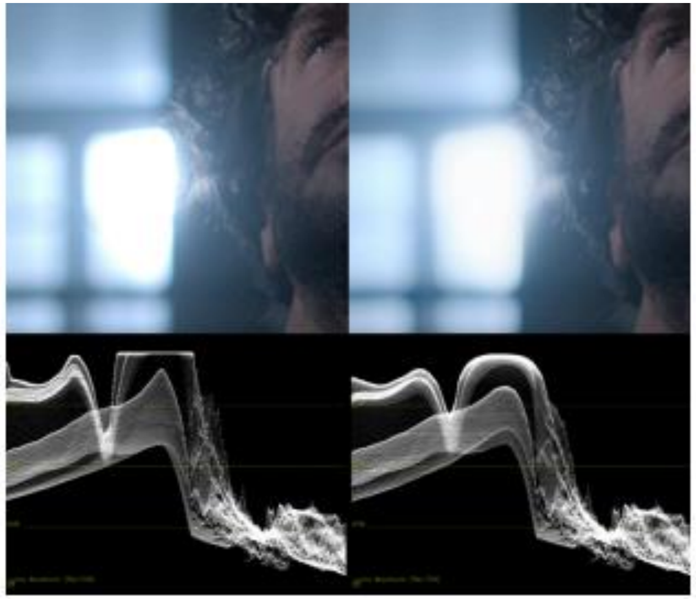
2. Apple Pro XDR
   - The monitor is HDR compatible, and it is factory calibrated. The white point has been fine-tuned

3. Vizio Smart TV
   - TV for visualization of HDR10+ / DolbyVision videos

Artifacts

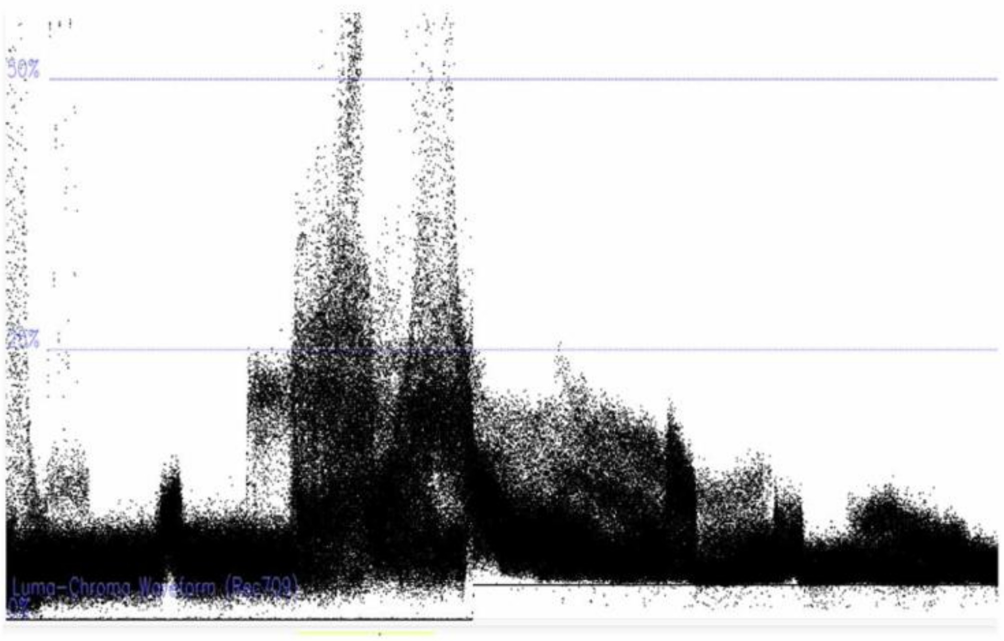
- Sensor Saturation might be revealed

- Unnatural sharp specular highlights, due to sensor saturation

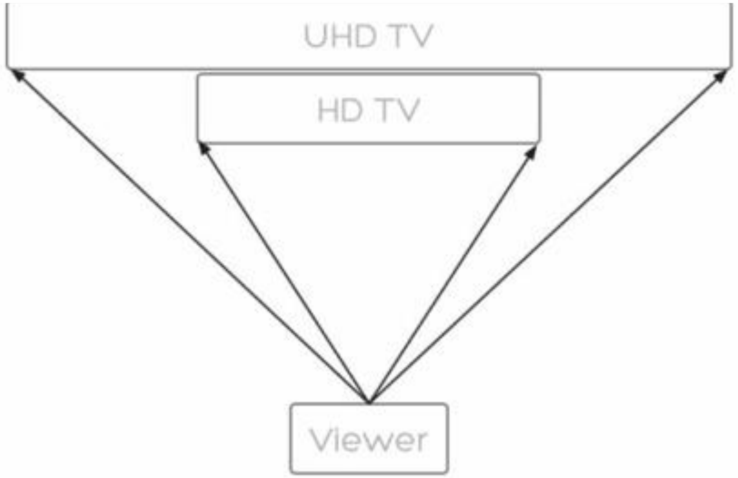


Artifacts

- With deeper blacks on the display, noise become a greater issue

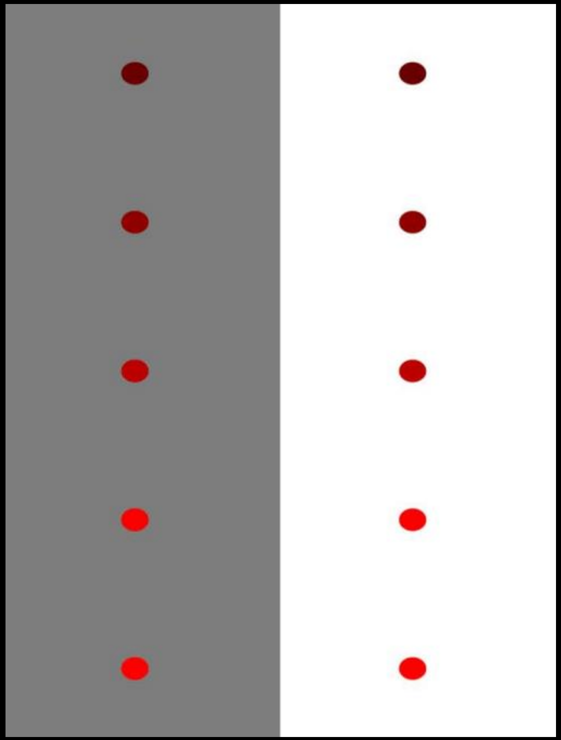


- Motion Judder depends on angular speed on the retina and contrasts…



Light Rendering

- Diffuse white as limit for surface colours
  - Where to put diffuse white?
  - Objects that are brighter than a fraction of diffuse white will appear fluorescebt or will look like light emitting objects (Evans on zero Gray)
  - This fraction is dependent on the hue and the purity of the colour



Light Rendering – Attention Steering

- SDR vs HDR can change the centre of focus
- Need to be in sync with story telling

Take aways

Take Aways

HDR can cover many different aspects.

HDR revolution takes place slowly because the whole pipeline has to be upgraded.

Mostly high lights are concerned by HDR. But it is a huge gap!

Back compatibility, smooth transition is extremely important for adoption.

The playback environment is very important.

HDR contents can be produced from:

- carefully hand craft color grading (cinema)
- strictly normalized (sub optimal) recommendations (TV, Broadcast)
- fully automatized (smartphone, mobile displays)

The display becomes smart to adapt to the viewing environment.

Some links

HDR: Understanding PQ HDR and HLG

https://www.lightillusion.com/what_is_hdr.html

Photo HDR, with example (to be viewed on HDR screen, not mobile for now, and with Chrome):

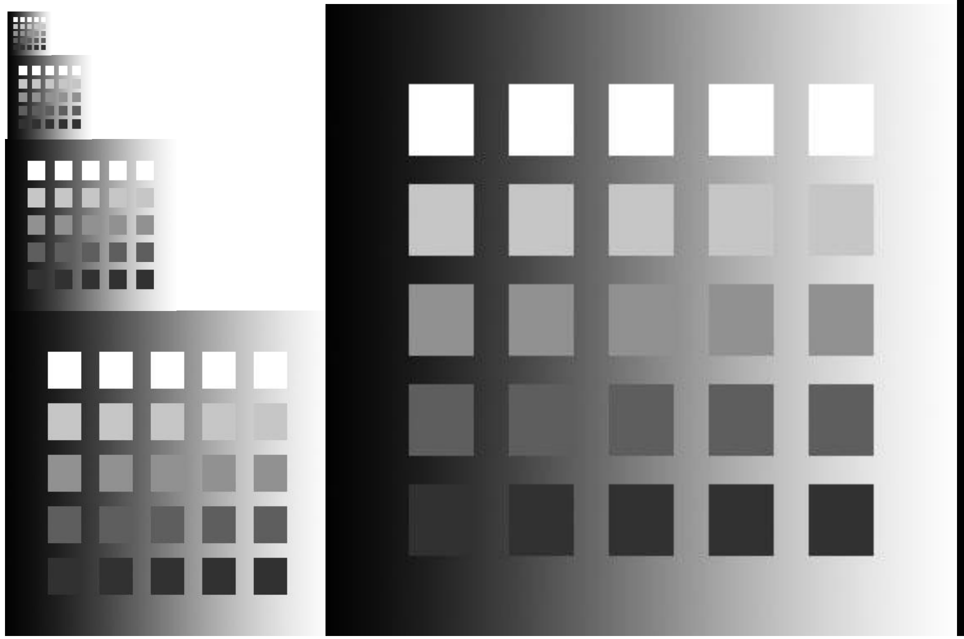
https://blog.adobe.com/en/publish/2023/10/10/hdr-explained

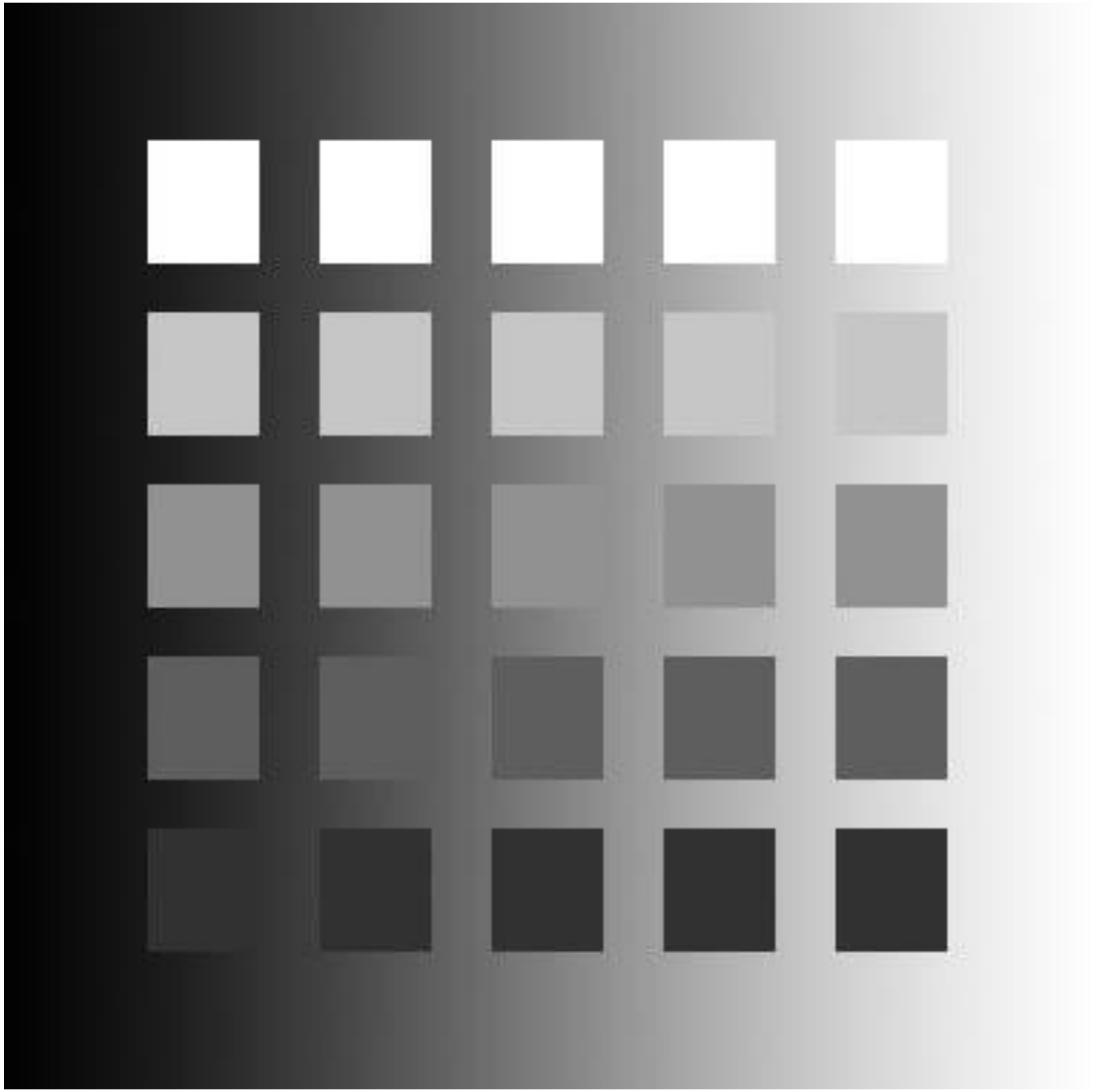
THANK YOU !

DXOMARK

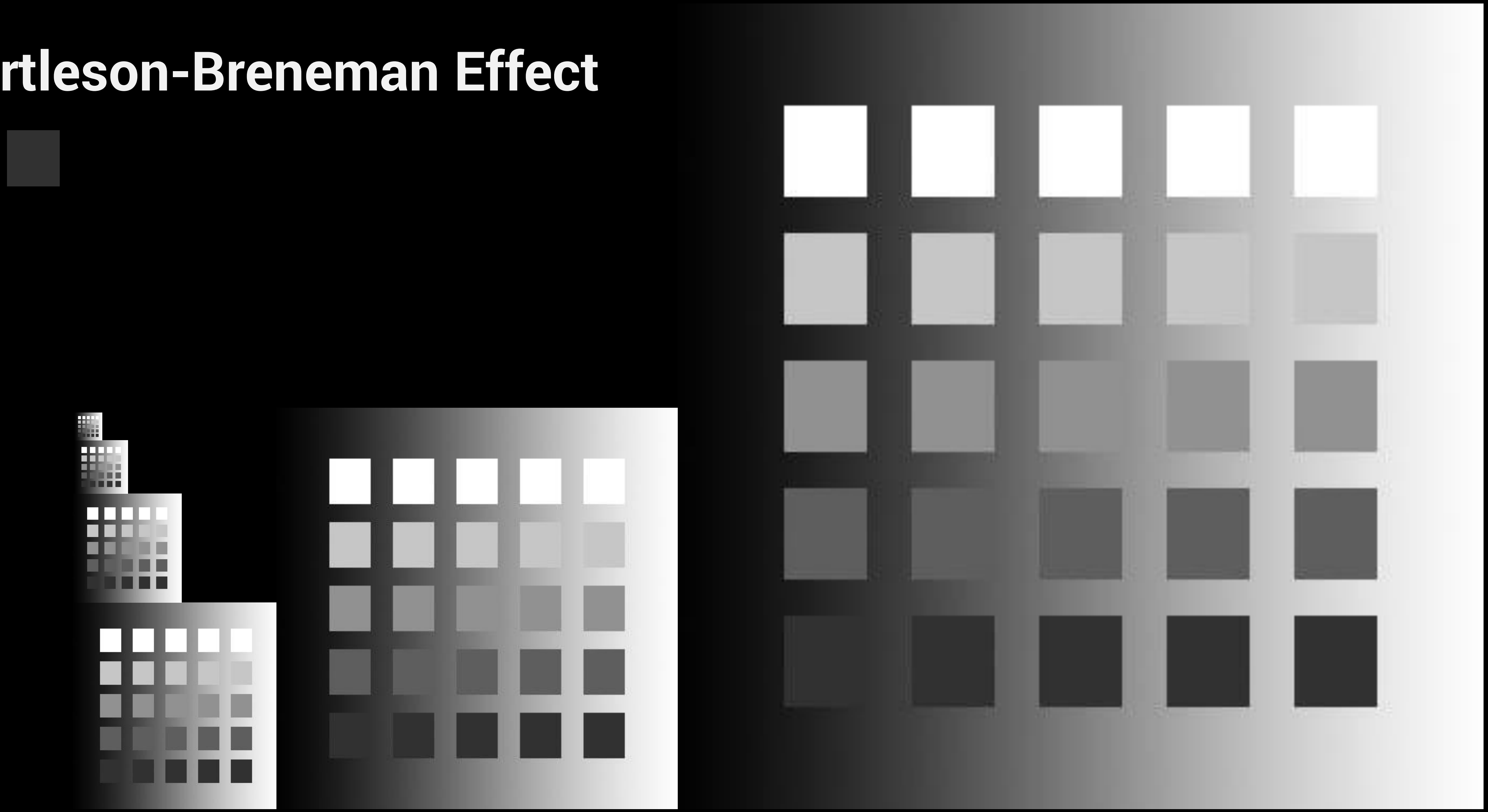
24-26, quai Alphonse le Gallo - 92100 Boulogne-Billancourt - France
www.dxomark.com

Bartleson-Breneman Effect





Bartleson-Breneman Effect



Bartleson-Breneman Effect